Natural Hazards 7: 121–132, 1993.

Probabilistic Seismic Hazard Evaluation in Underground Mines

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(Received: 11 February 1992; in final form: 1 October 1992)

Abstract. Stress concentrations produced by rock deformation due to extraction in underground mines induce seismicity that can take the shape of violent and quite dangerous rockbursts.

The hazard evaluation presented in this paper is based on a Bayesian probabilistic synthesis of information determined from mining situations during excavation, with previous and present data from microseismicity and seismoacustics.

The method proposed in this study is an example of 'time-dependent' on-line seismic hazard evaluation. All results presented were obtained retrospectiely for different underground coal mines in Poland and Czechoslovakia.

Key words. Induced seismicity, time-dependent seismic hazard, rockburst, coal mines, Poland, Czechoslovakia.

1. Introduction

Seismic events induced by underground mining (often called mine tremors) and rockbursts that sometimes occur along with them, reduce mining productivity, cause damage to the mine workings, to the earth surface, and are often a source of fatalities in mines. A wide review of seismicity induced by mining, including principal types of mine tremors, their focal mechanism and source modeling, source parameters and scaling relations, prediction and prevention, was presented by Gibowicz (1990 and references therein).

One of the directions in minimizing the risk of rockburst is the prediction of strong seismic events (Young 1989). Information about the seismic hazard in mines is obtained from different fields; geological and mining information, geophysical, geodetical and mining measurements and data evaluations (Spottiswoode, 1989; Gibowicz, 1990). This information is largely qualitative in character.

The method based on the time variation of the Gutenberg–Richter relation for tremor sequences on the longwall face (Lasocki 1989) and the method using the dependence of seismicity on the amount of extracted deposit, presented in this study, make possible a quantitative, on-line seismic hazard evaluation.

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Induced seismicity in underground mines is cause by rock deformation due to the extraction of some of its volume. Attempts to continuously evaluate this seismic hazard using the probabilistic dependence of seismic energy on extracted deposit volume have repeatedly been made for coal mines in Poland and Czechoslovakia, and preliminary evaluations have been published (Głowacka *et al.*, 1987, 1988, 1989, 1990; Głowacka, 1992b). The present work mentions only the most important assumptions on which calculations are based. The most general results obtained for four different mining regions in Poland and Czechoslovakia are presented.

The method should be regarded as a long-term prediction scheme, because it takes into acount energy accumulation in the rockmass. It gives best results for regions separated from other workings, in uncomplicated mining conditions. For evaluating short-term seismic hazard, and taking into account more complex mining conditions, additional information has to be used. In the second part of this study, the formalism on how to combine the results of long-term prediction, determined from the dependence between seismicity and extracted volume, with short- and medium-term prediction, determined from microseismicity and seismoacoustics, is presented. Examples for two mines in Poland are shown.

2. Seismic Hazard Evaluation Based on Exploitation

Let t be the time which has passed since the extraction began, and Δt the time interval under consideration, say, a month or a day, for which the seismic hazard is evaluated. Assume that for time $t - \Delta t$ (i.e. for the past) all information about seismicity and excavation is known.

The most probable sum of seismic energy $\langle \Sigma E(t - \Delta t, t\lambda)\rangle$ resulting from the excavation of the planned volume $\Delta V = V(t) - V(t - \Delta t)$, that will be released in unit time Δt, is expressed by the formula (Głowacka, 1992a)

$$\langle \Sigma E(t - \Delta t, t)\rangle = \{\Sigma E_T(t - \Delta t, t) e(\Delta t, b_t) + \Delta E(t - \Delta t)\}(e(\Delta t, b_t)), \quad (1)$$

where

$$\Sigma E_T(t - \Delta t, t) = C[V^B(t) - V^B(t - \Delta t)],$$

and the parameters C and B, are calculated on the basis of the formula (Kijko, 1985)

$$\Sigma E(t) = CV^B. \quad (2)$$

Equation (2) was obtained using the earlier solution of McGarr (1976) for the sum of seismic moment, and all formalism presented here can be expressed in terms of seismic moment. More details about (2) and its applications can be found in Głowacka and Kijko (1989) and Głowacka (1992b).

Parameters C and B of Equations (1) and (2) depend on the mining and geological situation of the rockmass and, since this situation is changing during the course of extraction, they are functions of time, $C = C(t)$, $B = B(t)$. Expression $e(\Delta t, b_t) = 1 - \exp(\Delta t \cdot b_t)$ is a function characterizing energy loading and relaxation as a function of time; it is equivalent to the assumption that the medium is described by a Kelvin–Voigt model. It was assumed that b_t, which characterizes the energy release time, is equal to 0.2 per day (Głowacka and Pilecki, 1991; Głowacka, 1991a); this assumption agrees with laboratory results (Scheidegger, 1982). The term $\Sigma E_T(t - \Delta t, t)e(\Delta t, b_t)$ describes energy loading in the rockmass as a result of extraction of ΔV, with loading function $e(\Delta t, t_t)$. The value $\Delta E(t - \Delta t)$ is the excess of seismic energy accumulated in the rockmass, at time $t - \Delta t$, and is evaluated at every state of calculation as a difference between the expected, $\langle \Sigma E(t - \Delta t) \rangle$ and observed, $\Sigma E(t - \Delta t)_o$, sum of released seismic energy: $\Delta E(t - \Delta t) = \langle \Sigma E(t - \Delta t) \rangle - \Sigma E(t - \Delta t)_o$; if $\Delta E(t - \Delta T) < 0$, then it is assumed that $\Delta E(t - \Delta t) = 0$.

Finally, the term $\{\Sigma E_T(t - \Delta t)e(\Delta t, b_t) + \Delta E(t - \Delta t)\}$ is the total seismic energy available for release according to $e(\Delta t, b_t)$, in the time interval Δt.

The most probable sum of seismic energy is calculated twice for every stage of seismic hazard evaluations; first from Equation (1), second assuming $\Delta E = 0$ in (1) (i.e. assuming no excess energy accumulation), expressed by

$$\langle \Sigma E(t - \Delta t, t) \rangle' = \{\Sigma E_T(t - \Delta t, t)e(\Delta t, b_t)\}(e(\Delta t, b_t)), \tag{3}$$

so the difference between values (1) and (3) can be easily interpreted as the excess energy accumulation (multiplied by $e(\Delta t, b_t)$). In Figure 1, the separation between curves 4 and 4a is a measure of excess energy accumulation.

The value of excavated area S was used, instead of excavated volume V, for the cases in which the height of workings is constant. At every stage of calculation, the values C, B, and ΔE are evaluated from the previous history of the dependence between seismic energy and the extracted deposit voume.

Moreover, it was assumed that the distribution of the released seismic energy, about the most probable energy described by formula (1), is a lognormal distribution (Głowacka, 1991, 1992b):

$$f_E(E) = 1/(E\sigma_x(2\Pi)^{1/2}) \exp(-((\ln(E) - m_x)/\sigma_x)^2/2), \tag{4}$$

where σ_x is the standard deviation of $\ln(E)$ and m_x is the most probable value of $\ln(E)$ (Benjamin and Cornell, 1970).

Let $P(E_j)$ denote the probability that the expected sum of seismic energy exceed the predetermined threshold E_j, i.e. $p(E_j) = P(\Sigma E \geqslant E_j)$, then

$$P(E_j) = 1 - \int_0^{E_i} f_E(E)\,\mathrm{d}E. \tag{5}$$

The seismic hazard will be understood as the sum of seismic energy released

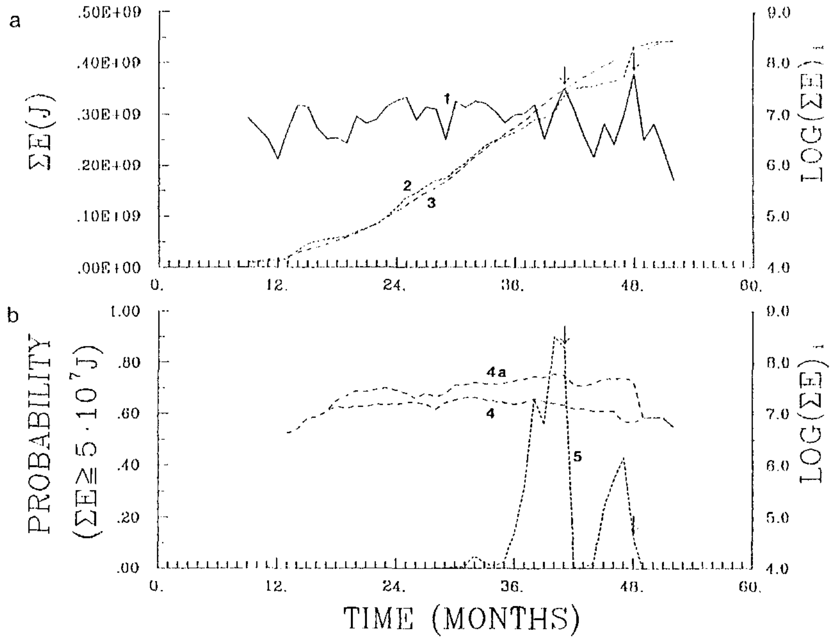

Fig. 1. Seismic energy versus time (in months) for the chosen region (five longwalls/seam 501) of the Wujek Coal Mine, for the period 1.10.1974–31.01.1979. Arrows mark the *strong tremors*, with energy larger than 1×10^7 J. Curves: 1 – monthly sums of seismic energy, referred to the right vertical axis; 2 – cumulative seismic energy, referred to the left vertical axis; 3 – energy calculated from relation (2); 4 – predicted seismic energy calculated from relation (3), 4a – predicted seismic energy (1); both 4 and 4a curves referred to the right vertical axis; 5 – probability of exceeding the energy 5×10^7 J (5). Modified from Głowacka, Syrek, and Kijko (1987).

during time Δt (1), or as the probability that the value of the seismic energy sum exceeds the threshold E_j (5). Since the energy is stored in the rockmass, the way of seismic hazard evaluation presented in the study, should be regarded as long-term prediction.

The algorithm was tested for four different coal mining regions excavated through caving. The time of extraction was about 5 years for every region. The catalogs of thousands of tremors within the local magnitude range 0.5–3 were analyzed. As an example, the results for five longwalls of the Wujek coal mine (Poland) can be seen in Figure 1.

The figure shows observed and predicted values of released seismic energy, and probability, changing with time in monthly intervals. Curve 1 illustrates the monthly energy sum (in Joules). Curve 2 represents the total energy sum, and curve 3 the theoretical relation (2) plotted for the last stage of calculations (that is, for $t - \Delta t$). Curves 4, 4a, and 5 illustrate the evaluation of seismic hazard: the most probable value of the energy sum expressed by relation (3) when $\Delta E = 0$ (curve 4); the expected value of energy (1) taking energy accumulation into account (curve 4a); and the probability (5) that energy 5×10^7 J is exceeded (curve 5).

Table I. Prediction on the basis of energy accumulation

Mine	E (J)	Number of tremors	Success	Failure	False alarm
Wujek	$10^7 \leqslant E$	2	2	0	0
Kleofas	$5 \times 10^6 \leqslant E \leqslant 10^7$	4	3	1	1
Kladno	$10^5 \leqslant E$	6	4	2	2
Doubrava	$10^7 \leqslant E$	6	5	1	2
		18	14	4	5

Strong shock (or tremor) is defined in this paper as a shock with energy greater than the mean level of expected energy (3) i.e. when no excess energy accumulation is taken into account. In Figure 1, this is the mean level of curve 4 and it is equal to 10^7 J. The arrows show the strongest shocks in the analyzed period. The probability increase (curve 5) and energy accumulation (the separation between curve 4 and 4a) preceding microearthquakes with energy greater than 10^7 J can be seen in Figure 1. Hundreds of tremors, in the analyzed area, with energy lower than the mean level of energy expressed by (3) result from extraction ΔV in the time interval Δt only, and they are not shown in the figure.

The results obtained for another three regions were similar. If the value of excess energy accumulated in the rockmass is treated as a measure of seismic hazard, the specification presented in Table I can be done. It can be seen that 14 out of 18 strong tremors were preceded by excess energy accumulation. A good correlation can be found (Figure 2) between the value of seismic energy E radiated in the strong tremors and the value of excess energy accumulated before them, ΔE, expressed by the formula $E = a \cdot \Delta E$. For the 14 tremors mentioned above, coefficient 'a' is equal to 1.0 ± 0.2. One tremor with energy 10^9 J (Kleofas* mine) was preceded by an accumulation five times smaller than the tremor energy. This probably resulted from the fact that the area of energy accumulation covers a region several times greater than the one analyzed (Głowacka, 1992a). However, the possibility of interaction between mine-induced and residual tectonic stresses for very strong events cannot be excluded (Gibowicz, 1990).

The above-presented method gives information on how much energy released in strong shocks can be expect (from ΔE) and how high is the probability $P(E_j)$ that the expected sum of seismic energy exceeds the predetermined threshold E_j. The threshold value E_j can be changed, but if too small a value is used (below the mean value (3) of energy released for a given Δt), the resulting probability will always equal unity, so information will be lost. In the following part of this study, only information $P(E_j)$ is used.

Accumulation of energy and the large probability of a strong tremor can last for several months (Figure 1). This is why the seismic hazard evaluation based on

* In the past the Kleofas mine (Poland, Upper Silesia) was named Gottwald, and can appear with both names in references.

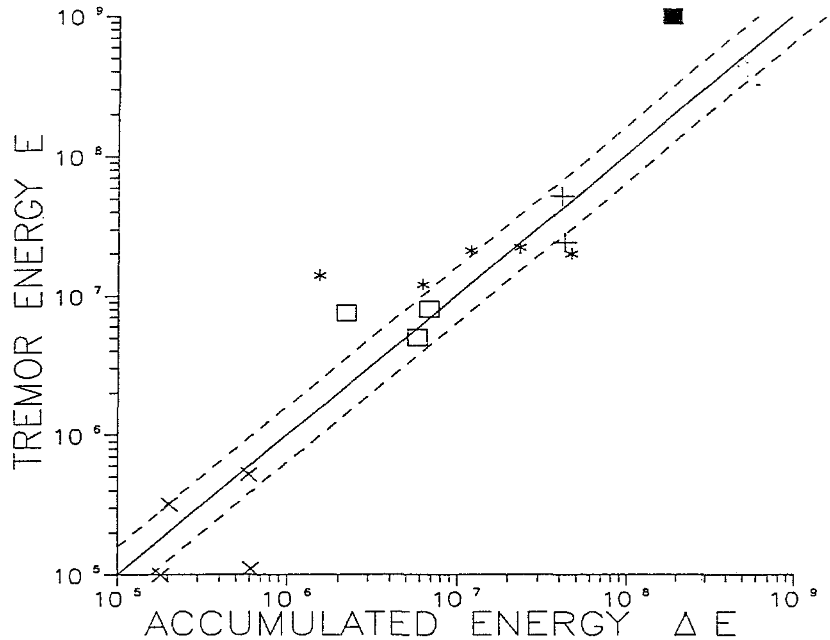

Fig. 2. Tremor energy E versus accumulated energy ΔE. Mines: Wujek (PL) +, Kleofas (PL) □, Gottwald (Kladno CSFR) ×, Doubrava (Ostrava CSFR) ∗. Tremor with energy 1×10^9 J (Kleofas mine ■) was not taken into account. The continuous line expresses the relation $E = a \cdot \Delta E$, dotted lines express $E = (a \pm \Delta a) \cdot \Delta E$.

the dependence of seismic energy on the extracted deposit volume should be regarded as long-term prediction. Fortunately, in mining we have information about seismic hazard from different sources (e.g. Spottiswoode, 1989; Gibowicz, 1990), which in some cases can be treated as short- or medium-term prediction. Having additional information is particularly important in complex mining conditions.

There are several ways of combining different methods of seismic hazard evaluation used in the prediction of strong earthquakes. The most popular method, if the results are to be presented in probabilistic form, is the Bayes method (Rikitake, 1976).

The purpose of this study is to show how to use the Bayes formula to evaluate the probability of a strong tremor of rockmass if at least two independent methods of seismic hazard evaluation are used.

3. The Probabilistic Synthesis

Let $P(E|A)$ denote the conditional probability that there will occur a tremor with energy greater than E, on the condition that an event A (a result of observation or evaluation) is registered. Then, on the assumption that all the probabilities have been calculated for a predetermined area S and a preset unit time Δt, the Bayes formula for two or more events takes the form

$$P(E|A, B \ldots) = \frac{P(A, B \ldots |E) \cdot P(E)}{P(A, B \ldots |E) \cdot P(E) + P(A, B \ldots |\bar{E}) \cdot P(\bar{E})}, \tag{6}$$

where $\bar{E}$ is the negation of event E (the nonoccurrence of a tremor with energy greater than E), $P(E)$ is called *a-priori* probability, and $P(E|A, B \ldots)$ is the *a-posteriori* probability of the event E.

Let

$$p_A = P(E|A), \quad p_B = P(E|B), \quad p_O = P(E), \text{ and } p = P(E|A, B \ldots);$$

then, on the assumption of conditional independence of two events A and B,

$$p(A, B|E) = p(A|E) \cdot p(B|E), \tag{7}$$

Equation (6) takes the form

$$(1/p - 1)(1/p_O - 1) = (1/p_A - 1)(1/p_B - 1) \tag{8}$$

which was independently derived by Aki (1981) and Utsu (1979). For a small time unit, the values p, p_O, p_A, p_B are small and it can be shown (Aki, 1981) that

$$p = p_O \cdot \frac{p_A}{p_O} \cdot \frac{p_B}{p_O} \cdot \ldots \tag{9}$$

The quantity p_A/p_O is called the *probability gain* (Aki, 1981) resulting from the detection of the anomaly A. The occurrence of the anomaly A increases the probability if $p_A/p_O > 1$.

Whether assumption (7) is realistic is not clear in practice (Rhoades, 1989a). Generally, one can state that precursors with different origin time are independent.

The present study will show the results of application of Equations (8) and (9) to two independent methods of continuous seismic hazard evaluation in mines.

The *a priori* probability p_O is calculated using the following equation:

$$p_O = n(E_j)/N, \tag{10}$$

where $n(E_j)$ is the number of time intervals Δt when a tremor with energy greater than E_j has occurred, and N is the number of these time intervals in the whole time period under consideration. In mining practice, the value of p_O can be evaluated using Gumbel's method (Kijko *et al.*, 1982).

The evaluation was performed for two mining longwalls. The first is the 11/507 longwall in the Bobrek mine (Głowacka and Lasocki, 1991). The time variation of the Gutenberg–Richter relation for the tremor sequences is used as a medium-term forecast. A detailed explanation of the method can be found in Lasocki (1989, 1990).

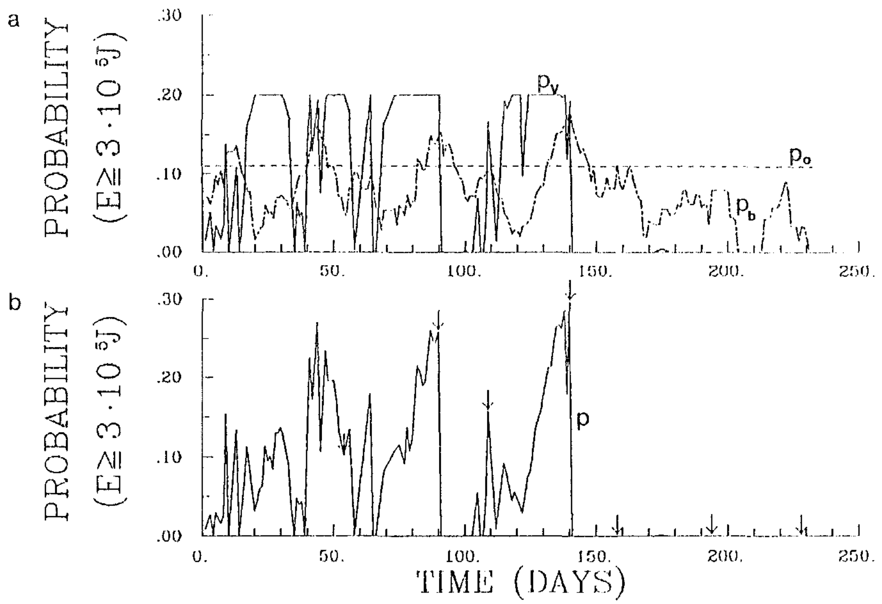

Fig. 3. Results of seismic hazard evaluation for longwall 11, Bobrek Coal Mine (Poland) for the period 04.09.1986–23.04.1987. Arrows mark the tremors with energy larger than 5×10^5 J. Modified from Głowacka and Lasocki (1991). (a) p_O – *a-priori* probability (10), p_V – predicted probability based on extracted deposit volume (1), p_b – predicted probability calculated using the Gutenberg–Richter relation. (b) p – *a-posteriori* probability calculated from relation (8).

The results are displayed in Figure 3. Figure 3a shows the probability p_O (calculated from (10)), p_V (calculated from (1) and normalized), and p_b (calculated from time variation of the Gutenberg–Richter relation). Figure 3b shows the probability p of occurrence of a tremor (8) of energy greater than 3×10^5 J during one day. The increase of probability p compared to p_V and p_b can be seen, before strong tremors, as a result of probability gain; it occurs where p_V/p_O and p_b/p_O are greater than 1. Four out of seven big tremors were preceded by increases of probability. Three out of seven tremors were not predicted. This was due to a p_V almost equal to zero for the final period of longwall 11.

If any one component of (8) is equal to 1, the synthetic probability p equals 1 also. One can state that Equation (8) increases the high values of probability, which agrees with results of Rhoades (1989a), and diminishes the small values of probability. Generally, the results of the method cannot be treated quantitatively but, rather, qualitatively. An increase of probability, or a long time with a high level of probability, seems to point out a dangerous situation.

The probability p_V equals almost zero for the second half of the analyzed period of longwall 11, Bobrek Mine, and it can result from the fact that another longwall was opened near the studied area, which probably increased the seismic activity. In a similar situation, the results of p_V could be improved if all the extracted area is taken into account, and if additional information, from different geophysical

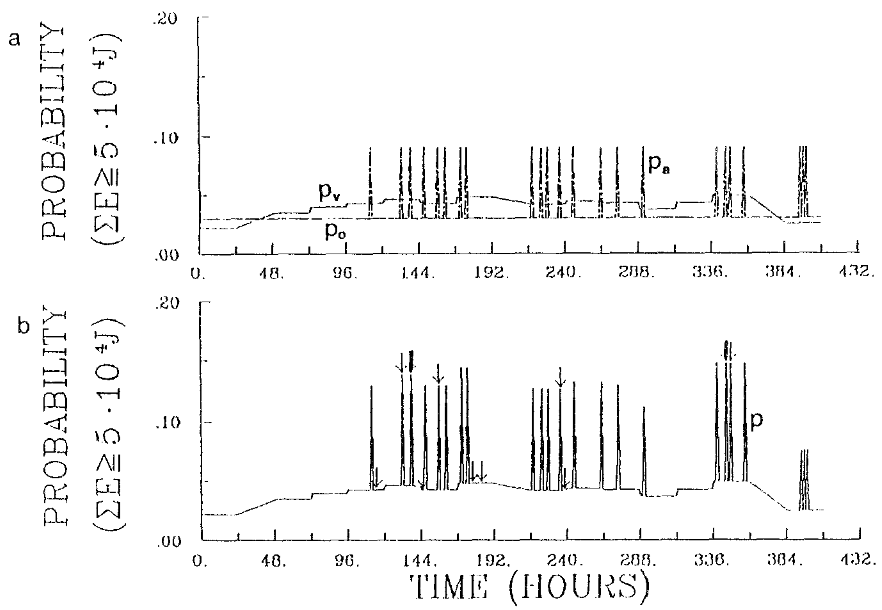

Fig. 4. Results of seismic hazard evaluation for J5/707 longwall in the Marcel Coal Mine (Poland) for the period 12.04.1986–28.04.1986. Modified from Głowacka, Pilecki (1991). (a) p_O – *a-priori* probability (10), p_a – probability evaluated using seismoacoustic activity, p_V – probability based on extracted deposit volume (1), (b) p – synthetic probability (9 or 8). Arrows mark the tremors with energy not less than 5×10^4 J. The bold arrows mark tremors with energy not less 1×10^6 J.

measurements is added. The prolem of p_V equal almost to zero, or to unity, can be removed by increasing the value of σ_x (Głowacka, 1991) in Equation (4). However, this method flattens the values of p_V, compared to other probabilities used in the synthesis.

The second analyzed region is the J5/707 longwall in the Marcel coal mine, where seismoacoustic activity was registered. Seismoacoustic anomaly, defined as at least a double increase in the number of impulses relative to the number registered over the previous hour, is proposed as a basis for short-term forecasting (Głowacka and Pilecki, 1991; Głowacka, 1989). The probability gain for a seismoacoustic anomaly was evaluated using the Aki (1981) method. Event E corresponds to the occurrence of a tremor or a sum of tremors with energy exceeding or equal to 5×10^4 J within one hour.

The results can be seen in Figure 4. This figure illustrates the product of probability gains for short- and long-term prediction obtained using Equation (9). The probability maxima before the strongest tremors ($E \geqslant 10^6$ J) can be seen. These resulted from the occurrence of strong events in periods, when p_V had maximas. The probability gain before strong events is equal to 5, while for seismoacoustic anomaly it was equal to 3. The synthesis of probability did not removed many false alarms, and did not increase the number of predicted events. The improvement can be achieved only by adding results of other geophysical, or mining, measurements. The results from use of Equation (8) give the same probability values (Głowacka, 1991). The assumption of small probability values, indispensable for Equation (9), is often unrealistic for mine conditions.

4. Summary and Conclusions

The purpose of the study was to show how to use the Bayes formula to evaluate the probability of a big tremor of rockmass in an underground mine, if at least two independent methods of seismic hazard evaluation are available. In the presented regions, three out of the four following independent methods were combined.

The first method used the statistical frequency of strong tremors.

The second method was based on the dependence of seismic energy on extracted deposit volume. This way of evaluation should be regarded as long-term prediction. A good correlation between the excess of accumulated energy and seismic energy released in strong tremors can be noticed. The efficiency of this method can be improved if all longwalls, located close to each other, where extraction is carried out at the same time, can be analyzed. This condition was not fulfilled in the case of the Bobrek Mine.

The problem of p_V almost equal to zero, or to unity, which is not convenient for probabilistic synthesis, can be removed by increasing the value of σ_x in Equation (4). However, this method flattens the results of p_V compared to other probabilities used for synthesis.

The third method of seismic hazard evaluation was based on the time variation of the Gutenberg–Richter relation. This can be treated as a medium-term forecast.

The next method of seismic hazard evaluation, used for synthesis, was short-term prediction based on seismoacoustic registration.

The method proposed in this work is an example of time-dependent, on-line seismic hazard evaluation.

The probability gain resulting from three stages of prediction increases manifold prior to strong tremors in both analyzed regions. It also seems important that the presented method yields information about periods of reduced seismic hazard compared to the standard statistical analysis based on frequency of tremors.

The method proposed in this study is a very convenient and easy tool for seismic hazard evaluation. However, the results indicate that the synthetic probability range is extended (small values are smaller while large ones are made larger) compared to the expected values of probability.

The virtue of the method is that it allows incorporation of outcomes from other geophysical or mining measurements, evaluations or expert opinions; for example tomography or information about seam edges, presented in probabilistic form.

Acknowledgements

An earlier version of this paper was presented at the XXth General IUGG Assembly in Vienna and at Reunion Geofisica Mexicana in Puerto Vallarta in

1991. This work was done under Professor Andrzej Kijko's (IGF Pol. Ac. Sc., Poland) attentive care for which the author is grateful. I would also like to thank Pawel Wiejacz (IGF, Poland) and Dr Alejandro Nava (CICESE, Mexico) for reviewing the manuscript and making helpful comments.

References

Aki, K.: 1981, A probabilistic synthesis of precursory phenomena, in D. W. Simpson and P. G. Richards (eds), *Earthquake Prediction, An International Review*, vol. 4, Amer. Geophys. Union, Washington D.C., pp. 566–574.

Benjamin, J. R. and Cornell, C. A.: 1970, *Probability, Statistics, and Decisions for Civil Engineers*. McGraw-Hill, New York.

Gibowicz, S. J.: 1990, Seismicity induced by mining, *Adv. Geophys.* **32**, 1–74.

Głowacka, E.: 1989, Application of the Bayes formula to the seismic risk evaluation in rockburst prone mines, *Proc. Fourth Internat. Sympos. Analysis of Seismicity and Seismic Risk*, Czechoslovakia, 4–9 Sept. 1989, pp. 550–555.

Głowacka, E.: 1991, Prediction of seismic activity of rockmass in view of course of exploitation, PhD thesis. (in Polish), Inst. Geophys. Pol. Ac. Sci., Warsaw.

Głowacka, E.: 1992a, Evaluation of seismic hazard taking into account the progress of mining, *Publ. Inst. Geophys. Pol. Ac. Sci.* M-16 (245), 262–277 (in Polish).

Głowacka, E.: 1992b, Application of the extracted deposit volume as a measure of deformation for the seismic hazard evaluation in mines, *Tectonophysics* **202**, 285–290.

Głowacka, E. and Kijko, A.: 1989, Continuous evaluation of seismic hazard induced by the deposit extraction in selected coal mines in Poland, *Pure Appl. Geophys.* **129**, 523–533.

Głowacka, E. and Lasocki, S.: 1991, Probabilistic synthesis of the seismic hazard evaluation in mines, *Acta Montana* (in press).

Głowacka, E. and Pilecki, Z.: 1991, Seismo-acoustic anomalies and evaluation of seismic hazard at the 'Marcel' Coal Mine, *Acta Geophys. Pol.* **39**, 47–59.

Głowacka, E., Rudajew, V., and Bucha, V.: 1988, An attempt at continuous evaluation of seismic hazard induced by deposit extraction for the Robert Field in Gottwald Mine in Kladno, Czechoslovakia, *Publ. Inst. Geophys. Pol. Acad. Sc.* **M-10**(213).

Głowacka, E., Stankiewicz, T., and Holub, K.: 1990, Seismic hazard estimate based on the extracted deposit volume and bimodal character of seismic activity, *Gerlands. Beitr. Geophys.* spec. issue 'Induced Seismicity' **99**, 35–43.

Głowacka, E., Syrek, B., and Kijko, A.: 1987, Dynamic evaluation of seismic hazard in selected area of the 'Wujek' coal mine (in Polish), *Acta Montana* **75**, 5–20.

Kijko, A.: 1985, Theoretical model for a relationship between mining seismicity and excavation area, *Acta Geophys. Pol.* **33**, 231–242.

Kijko, A., Dessokey, M., Głowacka, E., and Kazimierczyk, M.: 1982, Periodicity of strong mining tremors in the Lubin Copper Mine, *Acta Geophys. Pol.* **30**, 221–230.

Lasocki, S.: 1989, Some estimates of rockburst danger in underground coal mines based on the energy of microseismic events, in H. R. Hardy, Jr. (ed.), *Proc. Fourth Conf. Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, Pennsylvania State University 22–24 Oct. 1985, Trans Tech Publs, Clausthal, pp. 617–633.

Lasocki, S.: 1990, Prediction of strong mining tremors, *Zesz. Nauk. AGH, s. Appl. Geophys. Bull.* **7**, 110 (in Polish).

McGarr, A.: 1976, Seismic moments and volume changes, *J. Geophys. Res.* **81**, 1487–1494.

Rikitake, T.: 1976, *Earthquake Prediction*, Elsevier, Amsterdam.

Rhoades, D. A.: 1989a, Independence, precursors and earthquake hazard, *Tectonophysics* **169**.

Rhoades, D. A.: 1989b, Theory of multiple precursors: variation of hazard in time and space, *Proc. Fourth Internat. Sympos. Analysis of Seismicity and Seismic Risk. Bechyne, Czechoslovakia*, pp. 454–461.

Scheidegger, A. E.: 1982, *Principles of Geodynamics*, Springer-Verlag, Berlin, Heidelberg, New York.

Spottiswoode, S. M.: 1989, Perspectives on seismic and rockburst research in the South Africa gold mining industry: 1983–1987, *Pure Appl. Geophys.* **129**, 673–679.

Utsu,T.: 1979, Calculation of the probability of success of an earthquake prediction (in the case of Izu-Oshima-Kinkai earthquake of 1978), *Rep. Coord. Comm. for Earthquake Prediction*, pp. 164–166.

Young, R. P.: 1989, Editorial to Fred Leihton Memorial Workshop on Mining Induced Seismicity, August 30, 1987, in *Pure Appl. Geophys.* **129**, 285–294.