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DISPERSION OF FOCI – A POSSIBLE PRECURSOR OF STRONG TREMORS?

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ABSTRACT. A process of tremor generation taking place close to mining stopes is non–stationary. The seismic hazard, that is the probability of occurrence of a devastating event, varies then in time. Recent quantitative methods employed to evaluate the time–dependent seismic hazard in the local process of induced seismicity generation usually make use only of information contained in energies of a sequence of events.

Variations of tremor epicentre distribution in the non–stationary generating process were studied in the presented work. Two parameters of the distribution were controlled:

- directional coefficient A of the least–square straight line fit to a given number of successive events. The fitted line represented the temporary linear trend of epicentres;
- root–mean–square error ε of the straight line fit. This parameter accounted for a dispersion of epicentres with respect to the trend.

Series of A and ε parameters were evaluated for the sequences of tremors from different regions of various mines. Then statistical tests were performed to find out whether the values achieved for some days just before a strong tremor differ form the values obtained for randomly selected time periods. The analysis proved the significance of differences in the mean value, median and the shape of distribution of ε. The result suggests a possible usefulness of parameter ε as a precursor of strong events in the regions of mining works.

1. INTRODUCTION

Standard catalogues of mine tremors contain times of occurrences, coordinates of epicentres/hypocentres and magnitudes or energies of recorded events. In vast majority of recent algorithms of medium–to short–term prediction only times and magnitudes/energies are processed to evaluate time–dependent seismic hazard [Glowacka et al 1988; Lasocki 1993; Marcak 1993; Kijko, Funk 1994; Kalenda 1995]. Locations of foci of events if used, serve as complementary information to select a homogeneous, according to a predefined criterion, group of data.

Observations of the failure process taking place in the mining rockmass evidence, however, the fact that changes of the process towards increasing probability of strong event occurrence are correlated with, and possibly preceded by changes of spatial distribution of events. The feature, satisfactorily explained by physical theories of the fracture process [Marcak 1985; Ohnaka 1992] is in many cases used in qualitative prediction [Sato, Fujii 1988; Gerlach, Wyrobek 1991; Holub 1995].

The major limitation of the qualitative approach is its qualitativeness – its results are difficult to be compared and impossible to be expressed in terms of probability of oncoming events. Besides, the change of spatial distribution must be distinct to be traced qualitatively which means that the change in the event generation process must be significant. Hence the qualitative prediction based on studying variation of distribution of foci can be successful only when the process leading to the generation of strong event develops slowly and leaves exact prints in a form of weaker events.

The observed foci distribution variations accompanying the changes of seismic hazard in mining stopes encourage to construct quantitative prediction algorithms making use of the phenomenon. World–wide studies in this regard concentrated, in general, on various forms of cluster analysis of source locations to monitor grouping of seismic events [Frohlich, Davis 1990; Eneva, Young 1993; Kijko et al 1993; Stewart, Spottiswoode 1993] and on studies of the fractal dimension of source distribution [Turcotte 1989; Xie, Pariseau 1992; Stewart, Spottiswoode 1993]. The latter were supposed to account also for changes of the geometry of distribution. An expected tendency to co–planar clustering of sources in a zone of a future main fracture should show up as a decrease of the fractal dimension towards two in the case of three–dimensional studies or towards one if depth of sources is unavailable.

Unexpectedly the mentioned algorithms when applied to studying tremor data due to the local time–dependent failure process directly connected with mining operations delivered results far from being satisfactory. [Kijko et al. 1993] used cluster methods only along with the standard prediction method based on magnitude distribution. The independent parameters introduced by [Stewart, Spottiswoode 1993], built on the degree of clustering of sources and on fractal dimension of their spatial distribution were weakly or not related to the strong tremor hazard. The latter parameter behaved even opposite to the expectations based on theoretical considerations. [Trifu et al. 1993] also reported a lack of correlation between the fractal dimension of source locations and the probability of strong event occurrence expressed in terms of the Gutenberg – Richter b value. The evidence supporting opinions about the significant changes of the fractal dimension of source distribution before strong events in mines [Xie, Pariseau 1992; Trifu et al. 1993; Eneva, Young 1993] are merely qualitative. Our experience shows that this evidence cannot be positively verified by the correlation analysis [Mortimer, Lasocki 1995].

Regardless of specific explanations which could be given in any particular case there are some global reasons of little effectiveness of the foci distribution studies when applied to monitoring local seismic hazard changes in mining stopes. Mining operations in rockburst–prone mines are permanently accompanied by intensive seismic activity concentrated around the working front. The distribution of foci of these events, controlled mainly by the geometry of mining opening, overshadows the source distribution changes due to the change of fracturing process. Furthermore, estimators of fractal dimension are strongly biased and saturate for considerable numerous data samples [Mortimer, Lasocki 1995]. Usually the time interval needed to acquire the appropriately large data sample of induced seismicity events in local failure process is much longer than the preparatory period before strong event. Due to that the fractal dimension estimators, weakly sensitive to short period changes of foci distribution are also weakly sensitive to local seismic hazard variations. Finally, both the cluster and fractal methods, when used to construct independent indicators of hazard assume that all events are generated by a single fracturing process.

Within the presented studies we tried to find simple parameters which could be sensitive to short–term, second order variations of spatial distribution of sources of either single or multi–process origin and which could serve as statistical precursors of strong events. The parameters were to be defined on a sequence of locations of events occurring in a direct vicinity of mining works.

2. PARAMETERS OF SPATIAL DISTRIBUTION OF FOCI AND THEIR POSSIBLE VARIATIONS DUE TO CHANGES IN FRACTURING PROCESS

Since information on depth of events in local mining–induced processes is not very reliable and often unavailable we decided to analyse only epicentres of tremors.

Two parameters describing spatial distribution of epicentres were taken under consideration:

- the directional coefficient A of the least–square straight line fit $y = Ax + B$ to epicentre coordinates of the given number of successive events;
- the root–mean–square error ε of the straight line fit.

The parameters have only formal meaning and do not represent any permanent linear model of epicentre distribution. A and ε if evaluated for all recorded events account for the direction of overall elongation of the fracturing zone around the active front and its thickness respectively. As mentioned above, these values are fully controlled by the geometry of the front and remain more or less constant or undergo only long–term variations. However, when A and ε are estimated from short sequence of seismic events they will account for temporary alignment of epicentres and for a degree of this alignment respectively. Both parameters are easily and reliably estimated from small samples (down to three–case samples). Since the tendency to co–planar clustering of sources, i.e. collinear clustering of epicentres is expected in some cases to occur prior to strong tremor, A coefficient seemed to be a more reasonable choice than for instance the first moment of epicentre distribution.

One of the possible effects indicating an increase of the seismic hazard has already been discussed. The epicentres within the fracturing zone around the active front may tend to orientate more or less collinearly delineating the projection onto the (x, y) plane of a zone of future strong event. In this case A coefficient may change and ε coefficient should decrease. The opposite may be observed when the local stress field of the active moving front becomes disturbed by an additional factor e.g. mining remnants, old working edges or local faults. Such an additional seismicity concentrator at the beginning raises the probability for the event to locate farther from the working front. In this case the value of ε is expected to increase.

Certainly there is a large variety of complex cases which cannot be explained on the basis of the given simple models. One also may expect the presence of more than one interfering failure processes in the vicinity of mining works being responsible for the hazard variations. However, nearly all of them will have an effect on values of A and ε parameters.

3. ANALYSIS OF CAPACITY OF A AND ε PARAMETERS TO BE STRONG TREMOR PRECURSORS

The next problem concerning the introduced parameters is whether their expected changes caused by variations of hazard are significant enough so that the parameters could be used to identify times of increasing probability of strong event occurrence. This is the question about the potential of the parameters to be precursors of strong events. The necessary conditions for a quantity to be the statistical precursor of strong tremors are the following:

- it should significantly correlate with the probability of strong event occurrence,
- its values prior to strong event should significantly differ from its values evaluated at random moments.

The second condition implies the first one but in many cases only the first condition can be verified [Lasocki 1994].

The analysis of the capacity of A and ε parameters to be precursors was performed on tremor data from three rockbursting coal mines: Katowice, Halemba and Porabka from Upper Silesia, Poland. The studied data sequences were recorded close to longwall faces highly endangered by strong tremors and rockbursts. In the cases when an overall level of the event rate was variable the sequences were split into periods of more stable rate and the analysis was carried out on both the full sequence and the subsequences. Table 1 provides basic information about the studied data sequences.

TABLE 1. Induced seismicity sequences used to verify the capacity of parameters to be precursors of strong tremors

Sample No.	Mine	Longwall	Period of observation	Number of events	Mean event rate (per day)	Strong event definition [J]	Number of strong events	Mean strong event rate (per day)
I	Katowice	532	1.04.85 – 31.20.86	1519	2.62	$\geq$3e5	13	0.022
II	Katowice	533	7.10.85 – 30.09.86	696	1.94	$\geq$1e6	13	0.036
III	Katowice	536	16.08.92 – 15.03.93	1401	6.61	$\geq$3e5	6	0.028
IV	Katowice	537	16.03.93 – 15.01.94	1014	3.31	$\geq$3e5	10	0.033
V	Halemba	57	30.01.87 – 5.06.89	592	0.69	$\geq$4e5	53	0.062
VI	Halemba	57	13.03.87 – 26.10.87	89	0.40	$\geq$4e5	21	0.093
VII	Halemba	57	11.10.87 – 24.03.88	198	1.20	$\geq$4e5	23	0.139
VIII	Halemba	57	18.02.88 – 21.08.88	171	0.92	$\geq$4e5	8	0.043
IX	Porabka	755	6.06.91 – 12.07.93	2769	3.61	$\geq$1e5	17	0.022
X	Porabka	755	4.10.91 – 14.06.92	1498	5.87	$\geq$1e5	11	0.043
XI	Porabka	755	15.06.92 – 25.01.93	455	2.02	$\geq$8e4	9	0.040

Every data sequence was analysed separately. Values of A and ε parameters were calculated for every day on the basis of the last 30 events recorded on that and preceding days. The values of A and ε from five days before every strong tremor formed experimental groups (E–groups) respectively. Control groups (C–groups) were formed by A and ε values for randomly chosen days. In order to simplify further testing the sizes of both experimental and control groups were kept equal.

Differences in means, medians and distributions of the experimental and the control groups were then tested by means of the t–test, the Kruskal–Wallis ANOVA by ranks test and the Kolmogorow–Smirnow two sample test respectively. The results of the statistical analysis of the studied sequences are given in tables 2 and 3.

Table 2. The results of the comparison of A parameter values

Sample No	Sample size	T – test			Kruskal – Wallis test			Kolmogorow – Smirnow test
		E–group mean	C–group mean	Significance of difference of means	E–group median	C–group median	Significance of difference of medians	Significance of difference of distributions
I	43	−0.30	−0.28	0.77	−0.42	−0.29	0.79	0.22
II	47	−0.10	−0.10	0.24	−0.05	−0.11	0.36	0.40
III	26	−0.49	−0.31	0.19	−0.49	−0.27	0.17	0.49
IV	28	−0.01	−0.06	0.34	0.10	0.00	0.49	0.54
V	98	−0.22	−0.24	0.44	−0.19	−0.20	0.45	1.00
VI	17	−0.68	−0.62	0.26	−0.67	−0.60	0.08	1.00
VII	52	−0.02	−0.01	0.70	−0.03	−0.01	0.65	1.00
VIII	12	−0.21	−0.20	0.84	−0.23	−0.24	0.41	1.00
IX	65	0.18	0.20	0.68	0.19	0.12	0.57	1.00
X	43	0.21	0.20	0.88	0.21	0.14	0.65	0.12
XI	17	0.19	0.18	0.86	0.20	0.22	0.98	1.00

Table 3. The results of the comparison of ε parameter values

Sample No	Sample size	T – test			Kruskal – Wallis test			Kolmogorow – Smirnow test
		E–group mean	C–group mean	Significance of difference of means	E–group median	C–group median	Significance of difference of medians	Significance of difference of distributions
I	43	37.6	43.6	0.0011	35.8	42.8	0.0009	0.0003
II	47	54.8	50.9	0.0052	54.3	49.7	0.010	0.049
III	26	48.2	45.5	0.17	47.7	46.0	0.25	0.30
IV	28	29.0	32.5	0.020	27.1	33.4	0.024	0.002
V	98	79.4	87.3	0.000001	75.6	85.1	0.000007	0.0001
VI	17	93.9	98.0	0.041	96.4	98.7	0.083	1.00
VII	52	72.2	76.6	0.011	70.7	74.6	0.013	0.19
VIII	12	74.3	74.8	0.80	75.6	75.0	0.72	1.00
IX	65	40.7	56.0	0.029	37.8	44.6	0.016	0.014
X	43	39.2	51.0	0.019	37.4	41.1	0.0082	0.039
XI	17	38.1	37.6	0.87	37.5	36.4	0.35	1.00

While A parameter does not appear to differ much between E–groups and C–groups, all but three samples exhibit a significant difference in central tendency of ε. Hence the short–term dispersion of epicentres expressed by ε turns out to be a potential statistical precursor of strong tremor in local mining–induced seismicity. In the majority of cases the central tendency measures are greater in C–group than in E–group. This would suggest the event–ordering mechanism before the strong tremor. There are, however, two cases of reversed relation probably due to a more complex fracturing process behaviour leading to the generation of the strong event. Two from three cases of non–significant difference in ε came from poorly populated samples; thus these results are not very certain.

4. CONCLUSIONS

Two parameters were introduced to describe short–term arrangements of epicentres in the local induced seismicity–generation process taking place in the region of mining works, namely:

- the directional coefficient A of the least–square straight line fit to epicentre coordinates of the given number of successive events. The fit represented the temporary linear trend of epicentres;
- the root–mean–square error ε of the straight line fit representing the temporary dispersion of epicentres with respect to the trend.

The second occurred to change significantly prior to strong tremor thus can be used to build a precursor of devastating events.

The presented results came from a preliminary analysis only. Both the number of events to evaluate a single pair of A and ε values and the period before the strong event used while forming the experimental groups were taken arbitrarily without any reasonable justification. Certainly a deepened analysis including also other similar parameters defined on a sequence of epicentres is desirable before attempting to construct quantitative prediction methods based on the presented approach to the distribution of foci. However, the results give a clear indication of possible suitability of short–term foci dispersion in prediction of seismic hazard changes.

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