GEOLOGIA • 2009 • Tom 35 • Zeszyt 2/1 • 523–528

AN ANALYSIS OF GENERALIZED DISTANCES BETWEEN MINING-INDUCED SEISMIC EVENTS

Analiza uogólnionych odległości pomiędzy zdarzeniami sejsmicznymi indukowanymi działalnością górniczą

Zofia MORTIMER[1],
Barbara KORYTOWSKA[1] & Anna LASKOWNICKA[2]

[1] *Akademia Górniczo-Hutnicza, Wydział Geologii, Geofizyki i Ochrony Środowiska,*
Katedra Geofizyki;
al. Mickiewicza 30, 30-059 Kraków;
e-mail: mortimer@geol.agh.edu.pl, basia@geol.agh.edu.pl

[2] *Geofizyka Kraków Sp. z o.o.;*
ul. Łukasiewicza 3, 31-429 Kraków;
e-mail: anna.laskownicka@geofizyka.krakow.pl

Treść: Na bazie szeregów czasowych odległości epicentralnych lub hipocentralnych, energii i czasu pomiędzy kolejnymi zdarzeniami sejsmiczności indukowanej w kopalni złota i węgla konstruowane są fazowe przestrzenie zanurzone. Badane są odległości na trajektorii pomiędzy następującymi po sobie zdarzeniami, tak by wszystkie dostępne zmienne równocześnie oddziaływały na te wartości. Głównym problemem jest normalizacja zmiennych w taki sposób, aby można wyróżnić okresy poprzedzające zdarzenia wysokoenergetyczne. Aby ocenić czy proces przejawia trwałą korelację długookresową oszacowane zostały wartości wykładnika Hursta.

Słowa kluczowe: sejsmiczność, przestrzeń fazowa, odległość uogólniona, wykładnik Hursta, korelacja o długim zasięgu

Key words: seismicity, phase space, generalized distance, Hurst exponent, long-range correlation

INTRODUCTION

In searching for patterns of seismic activity preceding strong energy release, one can find research into the said in various studies of, among others, analyses of changes of scaling dimensions e.g. Radu *et al.* (1997), Mortimer (2002) or the correlation distances between events in sesimogenic areas e.g. Fröhlich & Davis (1990), Zaliapin *et al.* (2002).

It appears justifiable to extend the notion of the event distance to all the variables which are available. Such a possibility is given by the study of the seismic flux in the phase space of the seismogenic process. The coordinates of this space are physical variables which are independent of each other. We introduced a parameter which was the distances between the subsequent events on trajectories in seismic phase space so that all the available variables may simultaneously influence the reconstructed attractor.

As the real dimension of the phase space is unknown the studies were conducted in embedded spaces spanned on to the maximal number of variables which are measured in a particular case. It is standard that each seismic event is described by energy or the logarithm of energy, the epicentral coordinates or the hypocentral coordinates and the time interval between consecutive events but there may also be others like, for example, the seismic moment.

The data sets are taken from a coal mine in the Upper Silesian Coal Basin and a gold mine in South Africa. The characteristics of the data sets are given in table 1.

Table (Tabela) 1

Characteristics of the data sets

Charakterystyka danych

Region (its denotation) *Rejon (jego oznaczenie)*	Period of recording *Okres badawczy*	Number of events *Liczba zdarzeń*	logE range (energy in J) *Zakres logE (energia w J)*	Average activity (events/month) *Aktywność średnia (zdarzeń/miesiąc)*
Upper Silesian Coal Basin „Wujek” mine (1g_part3) *GZW KWK Wujek (1g_part3)*	02.88–10.88	990	3.00÷6.62	110
South Africa Western Deep Levels gold mine (F1_WDL) *Kopalnia złota (F1_WDL)*	01.93–12.93	916	3.00÷7.85	76

GENERALIZED DISTANCE CALCULATION

The seismic events i, k are treated as points on a trajectory in multidimensional phase space. In embedded spaces the number of the coordinates is defined by the number of the available registered seismic parameters. The generalised Euclidean distance d_{ik} is

$$d_{ik} = \left[\sum_{j=1}^{m} w_j^2 (x_{ij} - x_{kj})^2 \right]^{\frac{1}{2}} \tag{1}$$

where m is the number of the embedded space dimensions, w_j scales the X_j variable according to the physical sense of the individual variables.

The basic problem in the analysis of the mutual position of the events in multidimensional space is the transformation of the particular variables to obtain accordance or similarity of their scale.

We examined the variable standardisation controlled by the distribution of the particular variables during the period of “seismic silence”; this means the period without strong events’ occurrence in a given seismogenic area. It assumes that the ds values in such a period ought to cluster around the characteristic value for the given region.

In our previous study (Kortas *et al.* 2006, Laskownicka *et al.* 2006) we examined two types of variable normalization. The first one used the mean value and standard deviation of the particular variable, the second its maximal and minimal values. Both methods did not give significant differences in *ds* distribution which could have influenced the results of the analysis. The mean, the minimum and the maximum values of the generalized distance for the studied regions are presented in table 2.

Table (Tabela) 2

Descriptive statistics of the generalized distance ds

Statystyka opisowa odległości uogólnionych ds

Data set *Zbiór danych*	ds_{average} $ds_{\text{średnie}}$	$ds_{\min}$	$ds_{\max}$	Standard deviation *Odchylenie standardowe*
1g_part3	0.157	0.000	0.940	0.102
F1_WDL	0.452	0.000	1.075	0.193

Here we normalized the x_{ij} values of the X_j variable by

$$z_{ij} = \frac{x_{ij} - x_{j\min}}{x_{j\max} - x_{j\min}} \tag{2}$$

and tested different weights' w_j (equation 1) values for the seismic silence period. The aim was to find weights giving *ds* values that were clustered around the characteristic value for the examined region. After an analysis for both sets of the induced seismicity we chose the same values, $w_j = 0.2$, for all variables. This was not so in all the various mine cases we studied. The results for the subsets of F_WDL and 1g_part3, are illustrated in figure 1. The values of generalized distance d*s* averaged at an interval of 21 preceding events are displayed alongside the values of the logarithms of strong events' energy.

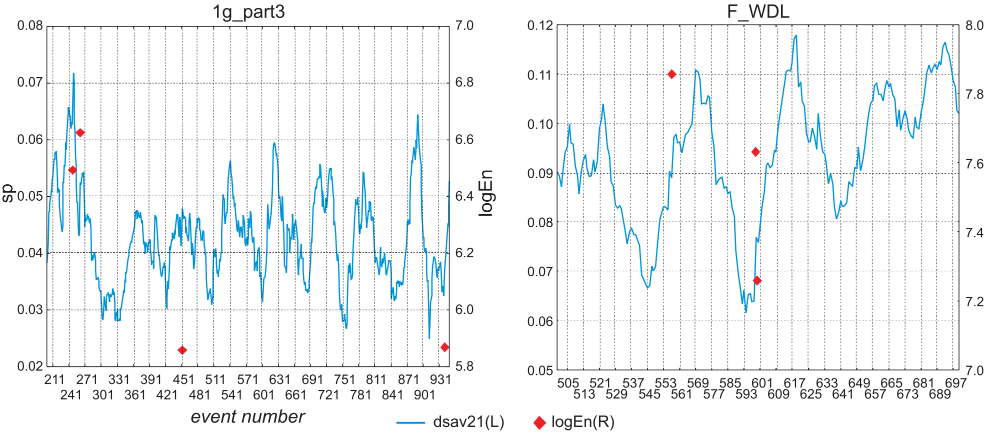

Fig. 1. Values of generalized distance *ds* averaged in an interval of 21 events and logarithms of strong events' energy logEn vs. event number

Fig. 1. Wartości odległości uogólnionej *ds* uśrednione w przedziałach 21 zdarzeń i logarytmy zdarzeń silnych logEN zestawione dla kolejnych numerów zdarzeń

For both sets of induced seismicity it may be found that almost all high energy events are related with rapidly decreasing values of *ds*. This statement is not valid in reverse: there are significant minima of the *ds* diagrams which are not associated with strong energy release. A great deal of the rapid decrease of the *ds* values is related to further strong energy occurrence.

HURST EXPONENT CALCULATION

The Hurst exponent, H, provides a measure of smoothness of fractal time series, based on the asymptotic behavior of the rescaled range, R/S, of the process. It is related to the auto-correlation function of the time series: $0.5 < H < 1$ indicates a persistent long-memory power-law correlation, $0 < H < 0.5$ indicates a power-law anti-correlation, $H = 0.5$ corresponds to a random walk.

We have estimated the Hurst exponent from the time series using a rescaled range analysis (Turcotte 1992).

The range $R(\tau)$ is the difference between the maximum $\xi(t)_{\max}$ and the minimum $\xi(t)_{\min}$ over the time period τ where $\xi(t)$ is the sum of deviations from the mean at time t

$$\xi(t) = \sum_{i=1}^{t} \left(z(i) - \langle z \rangle_{\tau} \right) \tag{3}$$

where $1 < t < \tau$ and $\langle z \rangle_{\tau}$ is the mean over the period τ.

The rescaled range $(R/S)_{\tau}$ is obtained by dividing $R(\tau)$ by the standard deviation $S(\tau)$. In discrete form

$$\left\langle \frac{R}{S} \right\rangle_n = \frac{R(n)}{S(n)} \tag{4}$$

where n is the number of points which fall in the period τ.

The average rescaled range $\langle R/S \rangle_n$ is calculated over a set of non-overlapping regions of length n. If $\langle R/S \rangle_n$ converges to a power function

$$\left\langle \frac{R}{S} \right\rangle_n \propto Cn^{H} \tag{5}$$

then the constant H is the Hurst exponent.

R/*S* analysis has been applied to earthquake studies, e.g. Xu & Burton (2006).

In table 3 we present Hurst exponents for time series of the generalized distance, the logarithm of energy, the intertime and the epicentral distance. Evaluated values are comprised in the range 0.63–0.74, which indicates positive correlations in the analyzed time series, suggesting long-memory process.

Table (Tabela) 3

Hurst exponents from time series: $H_{\mathrm{d}s.}$ – for the generalized distance, $H_{\log E}$ – for the logarithm of energy, $H_{\mathrm{d}t}$ – for the intertime, $H_{\mathrm{d}e}$ – for the epicentral distance

Wykładniki Hursta szeregów czasowych: $H_{\mathrm{d}s.}$ *– dla uogólnionych odległości,* $H_{\log E}$ *– dla logarytmów energii,* $H_{\mathrm{d}t}$ *– dla czasu pomiędzy zdarzeniami,* $H_{\mathrm{d}e}$ *– dla odległości epicentralnych*

Data set *Zbiór danych*	Hurst exponent			
	$H_{\mathrm{d}s}$	$H_{\log E}$	$H_{\mathrm{d}t}$	$H_{\mathrm{d}e}$
1g_part3	0.66	0.64	0.74	0.71
F1_WDL	0.67	0.65	0.63	0.63

A similar range of the H values was observed in the other mine cases we studied (This result confirms the non-random character of the seismic flow).

CONCLUSIONS

The distances between the subsequent events on trajectories in seismic phase space show the differentiation between particular seismogenic regions and significantly change when the event is "moving" on phase trajectories.

The character of the seismic flow observed in periods of seismic silence will determine further studies on the scaling of individual variables which form the generalized distance in such a way that one will be able to distinguish the periods preceding high energy events.

The Hurst exponent calculated for the studied variables is always greater then 0.6, which indicates positive correlations in the time series of the variables.

Acknowledgements: This work was financially supported by the Polish Committee for Scientific Research under Grant 4 T12B 051 26.

Praca była prezentowana na VII Konferencji Naukowo-Technicznej pt. „Geofizyka w geologii, górnictwie i ochronie środowiska" organizowanej z okazji jubileuszu 90-lecia AGH na WGGiOŚ.

REFERENCES

Fröhlich C. & Davis S.D., 1990. Single-link cluster analysis as a method to evaluate spatial and temporal properties of earthquake catalogues. *Geophysical Journal International*, 100, 19–32.

Kortas Ł., Mortimer Z. & Cichy A., 2006. An attempt to evaluate seismicity phase space dimension. *First European Conference on Earthquake Engineering and Seismology: a joint event of the 13th European Conference on Earthquake Engineering & 30th General Assembly of the European Seismological Commission*, Geneva (Switzerland) 3-8 September 2006: proceedings.

Laskowicka A., Mortimer Z. & Korytowska B., 2006. Badania dynamiki zdarzeń w przestrzeni fazowej procesu sejsmiczności indukowanej. *Miesięcznik Wyższego Urzędu Górniczego WUG*, 6, 142, 32–34.

Mortimer Z., 2002. Studies on the chaotic dynamics of mining induced seismicity. W: Ogasawara H., Yanagidani T. & Ando M. (eds), *Seismogenic Process Monitoring. Proceedings of a Japan-Poland Symposium on Mining and Experimental Seismology, Kyoto, Japan, November 1999*, Balkema, Lisse, 341–354.

Mortimer Z., Korytowska B. & Laskownicka A., 2006. Studies of mining induced seismicity phase space. 20 Years of Nonlinear Dynamics in Geosciences, June 11–16, 2006, Rhodos, Grees, *Aegean Conferences Series*, 24, 69, 92.

Radu S., Scioccatti M. & Mendecki A.J., 1997. Nonlinear dynamics of seismic flow of rock. W: Mendecki A.J. *Seismic Monitoring in Mines*. Chapman & Hall, Cambridge, 159–177.

Xu Y. & Burton P.W., 2006. Time varying seismicity in Greece. Hurst's analysis and Monte Carlo simulation applied to new earthquake catalogue for Greece. *Tectonophysics*, 423, 125–136.

Zaliapin I., Liu Z., Zöller G., Keilis-Borok V. & Turcotte D., 2002. On increase of earthquake correlation length prior to large earthquakes in Califoria. *Wycislitielnaja sejsmołogija*, Wyp. 33.