UNDERGROUND MINING ENGINEERING 40 (2022) 1-14 UDK 62
UNIVERSITY OF BELGRADE - FACULTY OF MINING AND GEOLOGY ISSN 03542904

Original scientific paper

CHARACTERIZATION OF GROUND OSCILLATIONS INDUCED BY UNDERGROUND MINING

Srđan Kostić[1], Nebojša Vasović[2]

Received: March 16, 2022 **Accepted:** May 02, 2022

Abstract: We examine ground acceleration during M1.5 and M2.0 seismic events induced by underground mining at Upper Silesian coal basin and Legnica Glogow copper mine, respectively, using methods of nonlinear time series analysis, in order to confirm its stochastic nature. Recorded time series are firstly embedded into the adequate phase space using the mutual information and box-assisted methods. After this, we performed stationarity test, by which we confirmed that the examined ground acceleration belongs to a group of stationary processes. Surrogate data testing is applied then, which resulted in following: (1) horizontal ground acceleration at Legnica Glogow copper mine represents stationary linear stochastic processes with Gaussian inputs, (2) ground acceleration at Upper Silesian coal basin originates from a stationary Gaussian linear process that has been distorted by a monotonic, instantaneous, time-independent non-linear function, (3) vertical ground acceleration at Legnica Glogow copper mine could not be ascribed to any of the examined processes, probably due to high level of instrumental or background noise. Low values of determinism coefficient ($\kappa \leq 0.7$), negative values of maximum Lyapunov exponent and quick saturation of neighboring points distance with the increase of embedding dimension indicate the absence of determinism in the observed ground acceleration time series

Keywords: underground mining, ground acceleration, time series analysis, stochasticity, determinism

1 INTRODUCTION

Analysis and characterization of recorded time series lies in the focus of both theoretical and applied science, since it enables verification and calibration of theoretical models, on one side, while it enables the possible prediction of the future development of the process under study, on the other side. The latter is of special concern, since catching the regularity of activity being monitored enables adequate design and planning of the further monitoring process, and engineering activities. In present paper, we analyze the recordings of the ground acceleration in order to confirm the existence of possible

[1] Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia
[2] University of Belgrade Faculty of Mining and Geology, Đušina 7, 11000 Belgrade, Serbia
E-mails: srdjan.kostic@jcerni.rs; nebojsa.vasovic@rgf.bg.ac.rs

determinism or deterministic chaos, which could indicate the possibility of predicting the ground motion during some of the future seismic events.

The construction of underground chambers and the advancement of the ore mining process inevitably disturbs the primary stress state, with changes being larger and more complex if the geomechanical conditions before the construction of the underground chamber were complex, or if the excavation process has not been adjusted to the natural conditions prevailing in that part of the rock mass. This stress redistribution, in some cases, can lead to earthquakes, where earthquakes of the greatest magnitude ($M \geq 4$) are usually caused by the redistribution of tectonic stresses in the immediate vicinity of the excavation. Previous research (Smith, et al., 1974) indicates that mining activity in the Earth's crust, in the general case, leads to a reduction in the magnitude of lithostatic pressure, by relieving rock mass, while at the same time, the horizontal stresses have also changed, as a consequence of the unloading and the Poisson effect (Wong, 1985). In the compressive tectonic field, which predominates in the Earth's crust, the effect of mining activity will cause movements along existing mechanically weakened zones (faults) before the failure, by reducing the vertically oriented maximum principal stress and increasing shear stress along faults. As a result, a seismically active rupture may occur, depending on the friction along the joints, and their orientation relative to the direction of the maximum principal stress. Previous research has shown that earthquakes in mines caused by reactivation of movement along faults are one of the most common occurrences of mining-induced seismicity (Cui, et al. 2004; Donnelly, 2006;). Moreover, these earthquakes are mostly the biggest events with the most severe consequences. The strongest earthquakes often reach magnitude M = 5, in exceptional cases up to M = 6. Impacts of such magnitudes with a focal depth of 1-2 km can cause earthquakes of intensity VI-VIII degrees according to the Modified Mercalli Scale (Zembaty, 2011).

Mining-induced seismic events have been reported throughout the world extensively in the last 40 years (for review of mining induced seismic events, one should check the work of Kostić, 2013). For mining-generated earthquakes in Poland, Gibowicz (1984) identified focal mechanisms for four major earthquakes registered in three different mining areas in Poland. Two earthquakes, the first of magnitude ML = 4.5, which occurred on June 24, 1977, between two copper mines in the Lubin area, and another, of magnitude ML = 4.3, which occurred on September 30, 1980, at the Shombierki Coal Mine in the Upper Silesian Basin, were the result of a normal fault, with different extensions to the north and northwest. In the United States, the best documented cases of fault earthquakes have been reported in the lead, silver, and zinc mines in the Couer d'Alene area of northern Idaho, as well as in the coal mines in the Wasac and Beech Cliffs areas in central Utah (Zoback, Zoback, 1989), primarily due to the proximity of the tectonic plate boundary along the Pacific coast and the high degree of seismicity. In eastern Canada, in the Sadbury Basin, in the deep mines of metallic minerals, numerous mining earthquakes have been registered (Wetmiller, et al., 1990). Milev et al (1995) analyzed 2017 mine-induced seismic events with magnitudes in the range of $0.0 < M <$

3.1 at East Rand Proprietary Mines, in the period 1992-1993. McGarr and Fletcher (2005) developed ground-motion prediction equations relevant to shallow-mining induced seismicity in Rtial Mountain Area (USA), with magnitude up to 2.17. Fritschen (2010) analyzed mining-induced seismicity in Saarlan, Germany, considering the M4 seismic event induced by the coal extraction in the Primsmulde field. Lizurek et al. (2015) analyzed ML4.2 seismic event at the Legnica Glogow Copper district, which occurred in 2013 along an inactive fault. Emanov et al. (2021) examined M6.1 seismic event near the Bachat open-cast coal mine in Kuzbass (Russia) in 2013, which is currently considered as the world's largest man-made earthquake related to the extraction of solid minerals.

In present paper, we analyze ground oscillations induced by underground mining at two mine locations in Poland: Upper Silesian coal mine and Legnica Glogow copper mine. Recorded oscillations are examined by invoking methods of nonlinear time series analysis, in order to confirm the stochastic nature of the mining-induced ground oscillations. Methods of nonlinear time series analyzes for confirming determinism / stochasticity have been successfully applied before (Kodba et al., 2005; Kostić et al., 2013).

Paper is structured as follows. In Section 2 we describe the applied methodology, while the main results of the conducted research are given in Section 3. Discussion and conclusion are provided in the final section of the paper.

2 DATA ANALYZED AND APPLIED METHODS

We examine ground oscillations induced by underground mining at Upper Silesian coal basin (M1.5 seismic event) and at Legnica Glogow copper mine (M2.0 seismic event). Typical acceleration time series for these events is given in Figure 1.

In order to conduct this analysis, we had to embed the observed scalar series into the appropriate phase space: the optimal embedding delay is calculated using average mutual information method, while the minimum embedding dimension is examined by box-assisted method. With the observed series properly reconstructed in phase space, we were able to conduct a stationarity test, which is a necessary prerequisite for a random dataset. As a next step in our analysis, we conducted the surrogate data testing, by assuming that: (1) the observed data are independent random numbers drawn from some fixed but unknown distribution; (2) data originate from stationary linear stochastic process with Gaussian inputs; (3) recordings originate from a stationary Gaussian linear process that has been distorted by a monotonic, instantaneous, time-independent non-linear function (Perc et al., 2008). For this purpose, we generated 20 surrogates. Then, in order to compare the original data and generated surrogates, we calculated the zeroth-order prediction error ε. If this error for the original dataset (ε_0) is smaller in comparison to the calculated error for surrogate data (ε), then a null hypothesis can be rejected. On the other hand, if $\varepsilon 0 > \varepsilon$ at any instance of the test, the null hypothesis cannot be rejected.

Usually, more than one wrong result out of 20 is not considered acceptable. For testing the third null hypothesis, Since the function is unknown in this case, the procedure for forming surrogate time series (AAFT procedure - phase randomization procedure with adjusted amplitude) consists of the following. First, the data of the initial time series are scaled to match the Gaussian distribution (effect of an unknown nonlinear function). The phase randomization procedure described in the previous step is then applied. After applying the inverse Fourier transform, the obtained surrogate data is finally scaled again to match the distribution of the initial time series. This procedure is repeated for each surrogate time series, but each time with a different phase in the phase randomization procedure. However, since the inverse Fourier transform does not provide a completely reconstructed time series, primarily in terms of power spectrum (which is with more noise), the amplitude of Fourier transforms is adjusted as follows (IAAFT procedure - iterative phase procedure randomizations with adjusted amplitude). Let $|s_k|$ be the desired amplitudes of the Fourier transform of the initial time series. Let us perform the phase randomization procedure, when the obtained surrogate Fourier transform is further changed by comparing the amplitudes of the Fourier transform of the initial and surrogate time series: $s_k'' = s_k' |s_k| / |s_k'|$. This step is repeated until the amount of noise in the power spectrum is reduced to an acceptable level. After performing the inverse Fourier transform, the obtained surrogate time series is compared with the initial time series.

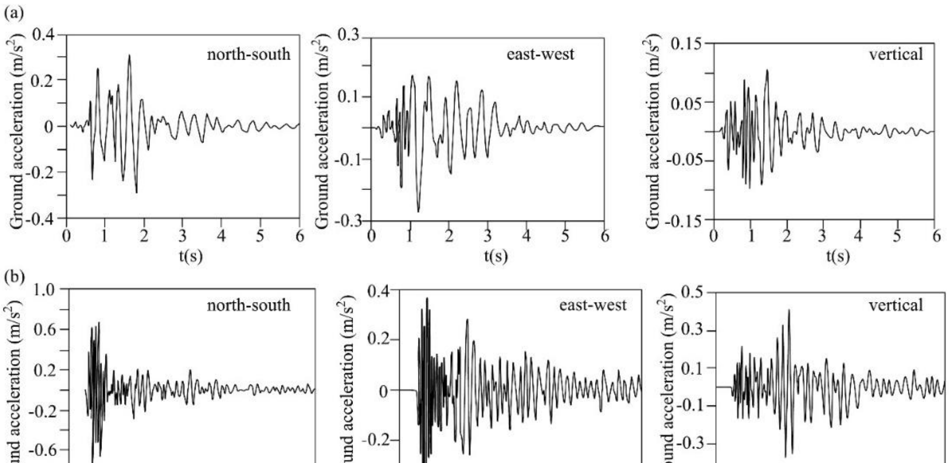

Figure 1 Typical ground acceleration time series, for M1.5 seismic event at Upper Silesian coal basin (a) and for M2.0 seismic event at Legnica Glogow copper mine (Dulinska and Fabijanska, 2011).

As a final step in the performed time series analysis, we applied a determinism test, which is based on the assumption that if a time series originates from a deterministic process, it can be described by a set of the first-order ordinary differential equations, whose vector field consist solely of vectors that have unit length. In other words, if the system is deterministic, the average length of all directional vectors κ will be 1, while for a completely random system, $\kappa \approx 0$.

3 RESULTS

Recorded time series are firstly embedded into the corresponding phase space, by calculating minimum embedding dimension and optimum embedding delay. For three directions of ground oscillations, results of calculation of optimum embedding delay are shown in Figure 2. As it could be seen, optimum embedding delays for north-south, east-west and vertical direction are τ=8, τ=10 and τ=12, respectively, at Upper Silesian coal basin, and τ=9, τ= 8 and τ=14, respectively at Legnica Glogow copper mine. Regarding the values of minimum embedding dimension, one commonly uses false nearest neighbor technique; however, it was shown by previous studies that results of FNN technique could lead to ambiguous results, especially in the case when relatively small dataset is analyzed. In present case, application of FNN technique results in the increase of embedding dimension with the rise of percentage of false nearest neighbors, so minimum embedding dimension could not be determined by using this method. Therefore, we invoke the box-assisted method proposed by Schreiber (1995). According to this method, minimum embedding dimension for the recorded ground acceleration in north-south, east-west and vertical direction is m=11, m=4 and m=4, respectively, for the location of Upper Silesian coal basin, while for the same directions is equal to m=3, m=5 and m=8, respectively, for the location of Legnica Glogow copper mine.

Having determined the minimum embedding dimension and the optimum embedding delay, we further conduct stationarity, in order to examine whether the recorded time series represent stationary process, i.e. to examine whether different non-overlapping segments of the time series have different dynamical properties, or the system parameters were constant during the process. It is clear form Figure 3 that most of pairs exhibit low to moderate cross-prediction error, confirming the stationarity of the examined time series. In particular, for recorded time series at Upper Silesian coal basin, for north-south direction 95.7% of pairs is with cross-prediction error $\varepsilon < 0.25$, for east-west direction 91.1% is with $\varepsilon < 0.16$, and for vertical direction 89.04% is with $\varepsilon < 0.08$. Similary, for ground acceleration time series recorded at Legnica Glogow copper mine, for north-south direction 94.02% of pairs is with cross-prediction error $\varepsilon < 0.6$, for east-west direction 94.96% is with $\varepsilon < 0.26$, and for vertical direction 94.09% is with $\varepsilon < 0.28$. Since all cross-prediction errors differ maximally by a factor of 2, we can clearly refute non-stationarity in the studied time series.

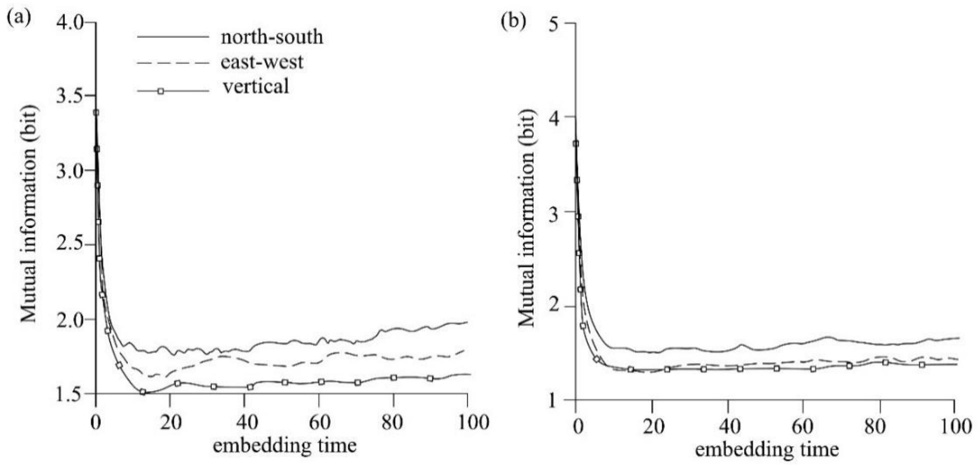

Figure 2 Results of mutual information method for ground oscillations at: (a) Upper Silesian coal basin, (b) Legnica Glogow copper mine.

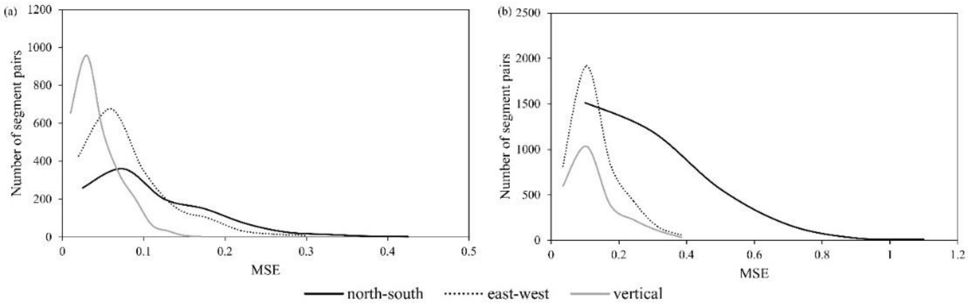

Figure 3 Histograms of cross-prediction errors for stationarity test: (a) Upper Silesian coal basin; (b) Legnica Glogow copper mine.

Surrogate data testing is further applied in order to classify the examined time series more closely. Results of testing the first null hypothesis are presented in Figure 4. As it is clear, hull hypothesis could be rejected for recordings made in the north-south direction at both examined locations, since $\varepsilon_0 < \varepsilon$ for each time step n. Qualitatively the same results are obtained for remaining two directions at both locations.

Regarding the results of testing the second null hypothesis, it is clear from Figure 5(a) that null hypothesis could be rejected for ground acceleration recorded at all three directions at Upper Silesian coal basin, since ε_0 is well within ε for each time step n. As for the results at Legnica Glogow copper mine, $\varepsilon_0 < \varepsilon$ for each time step n for the ground oscillation in horizontal plane (in both directions: north-south and east-west), while ε_0 is well within ε for each time step n for vertical oscillations (Figure 5b). Therefore, ground acceleration recorded in horizontal plane at Legnica Glogow copper mine could be characterized as stationary linear stochastic processes with Gaussian inputs.

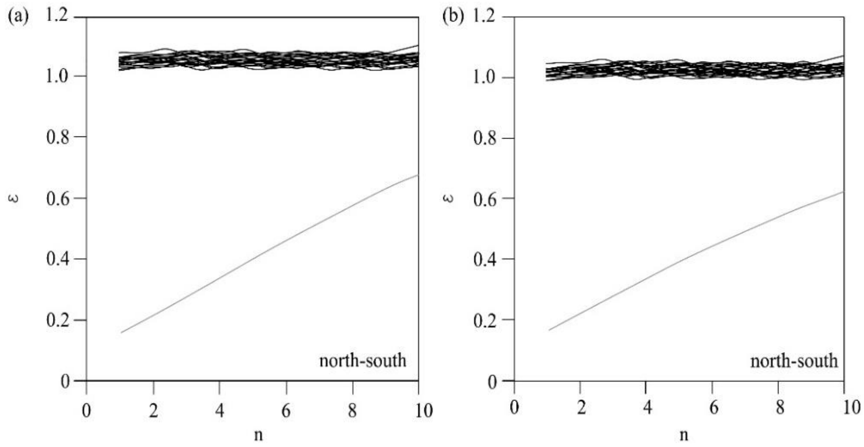

Figure 4 Surrogate data testing – I null hypothesis, for north-south direction at: (a) Upper Silesian coal basin, (b) Legnica Glogow copper mine. Qualitatively same results are obtained for other two directions. Gray line denotes the prediction error for the original time series (ε_0), while black lines denote error propagation for the surrogate time series (ε).

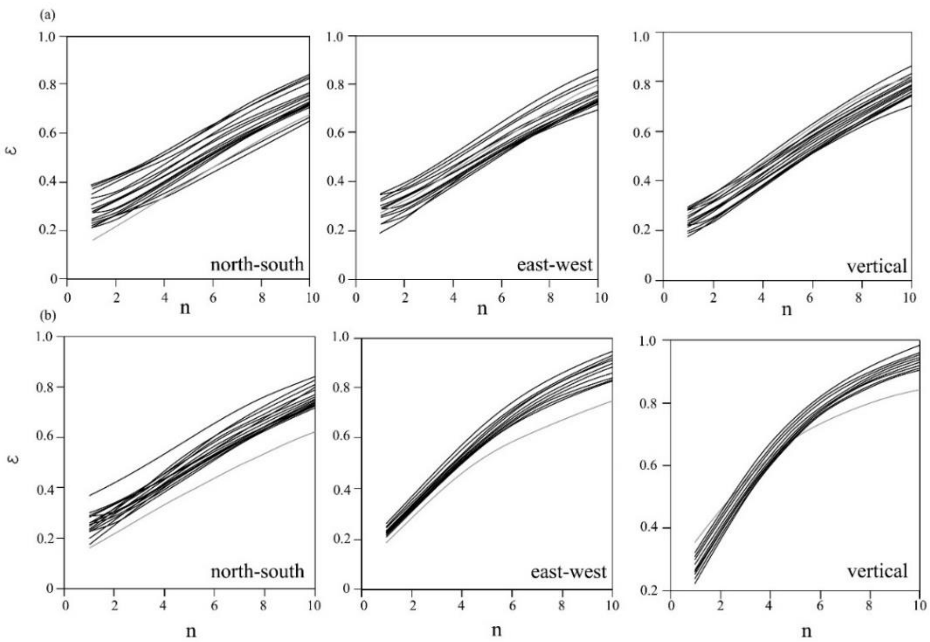

Figure 5 Surrogate data testing – II null hypothesis: (a) Upper Sileasian coal basin; (b) Legnica Glogow copper mine. Gray line denotes the prediction error for the original time series (ε_0), while black lines denote error propagation for the surrogate time series (ε).

Results of testing the third null hypothesis are shown in Figure 6. As it could be seen, third null hypothesis could not be rejected only for the recordings made in north-south direction at Upper Silesian coal basin. For all other recordings, ε_0 is well within ε for each time step *n*, so null hypothesis could be rejected. In case when IAAFT procedure is implemented than third null hypothesis for ground oscillations at Upper Silesian coal basin could not be rejected, while ε_0 is well within ε for each time step n for vertical oscillations at Legnica Glogow copper mine (Figure 7). This indicates that ground acceleration at Upper Sileasian cola basin could be characterized as originated from a stationary Gaussian linear process that has been distorted by a monotonic, instantaneous, time-independent non-linear function. Ground acceleration in vertical direction at Legnica Glogow copper mine could not be ascribed to any of the examined processes, probably indicating high level of instrumental or background noise. Moreover, results of surrogate data testing indicate the presence of colored noise, which is in such natural systems commonly expressed as additive noise.

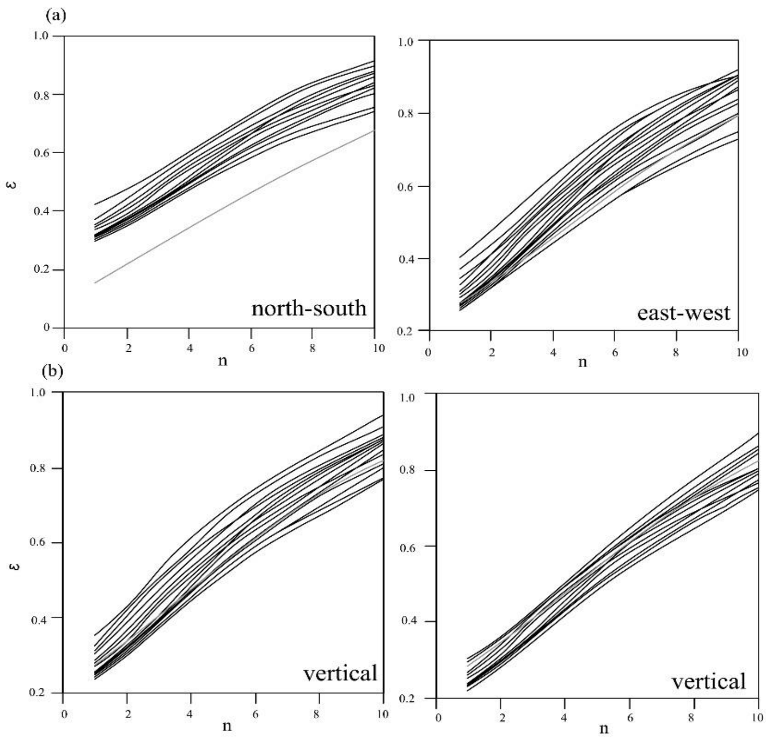

Figure 6 Surrogate data testing – III null hypothesis with AAFT procedure: (a) horizontal plane, location Upper Silesian coal basin; (b) vertical direction: Upper Sileasian coal basin (left) and Legnica Glogow copper mine (right). Gray line denotes the prediction error for the original time series (ε_0), while black lines denote error propagation for the surrogate time series (ε).

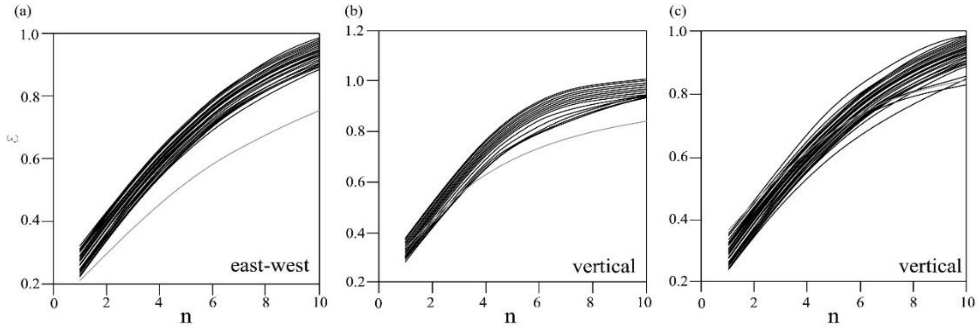

Figure 7 Surrogate data testing – III null hypothesis with iAAFT procedure: (a) east-west direction (Upper Silesian coal basin), (b) vertical direction (Upper Silesian coal basin); (c) vertical direction (Legnica Glogow copper mine). Gray line denotes the prediction error for the original time series (ε_0), while black lines denote error propagation for the surrogate time series (ε).

Determinism test, for the obtained embedding dimension and embedding delay, resulted in relatively low values of determinism factor κ=0.8, κ=0.6 and κ=0.76 for ground acceleration in NS, EW and V direction at Upper Silesian coal basin, respectively, and κ=0.6, κ=0.67 and κ=0.71, for the same directions at Legnica Glogow copper mine. As it could be seen, values of determinism coefficient are significantly smaller than 1, indicating relatively high level of stochasticity in the recorded ground acceleration time series.

Concerning the impact of variability of embedding dimension on determinism coefficient, additional analyzes confirmed that in the range of embedding dimension [2,11] determinism coefficient changes in the range [0.60-0.92], for Upper Silesia, and [0.67-0.92] for Legnica Glogow. Considering this, it is very important to determine the value of minimum embedding dimension in a proper way.

As a final step, we calculated largest Lyapunov exponent, using Wolf's method (1985) and Rosenstein method (1993). As it could be seen from Figure 8(a), largest Lyapunov exponent asymptotically approaches the negative value, indicating the absence of deterministic chaos in the system under study. In figure 8(b) according to Rosenstein method, curve S(Δn) shows sudden jump in the staring time t≈0 and it saturates very quickly with the increase of embedding dimension, indicating the stochastic nature of the analyzed ground acceleration time series. For this method to apply, we chose 1000 reference points, where each point is surrounded with minimum 10 points, while the distance between neighboring points is in interval ε=0.01-0.05.

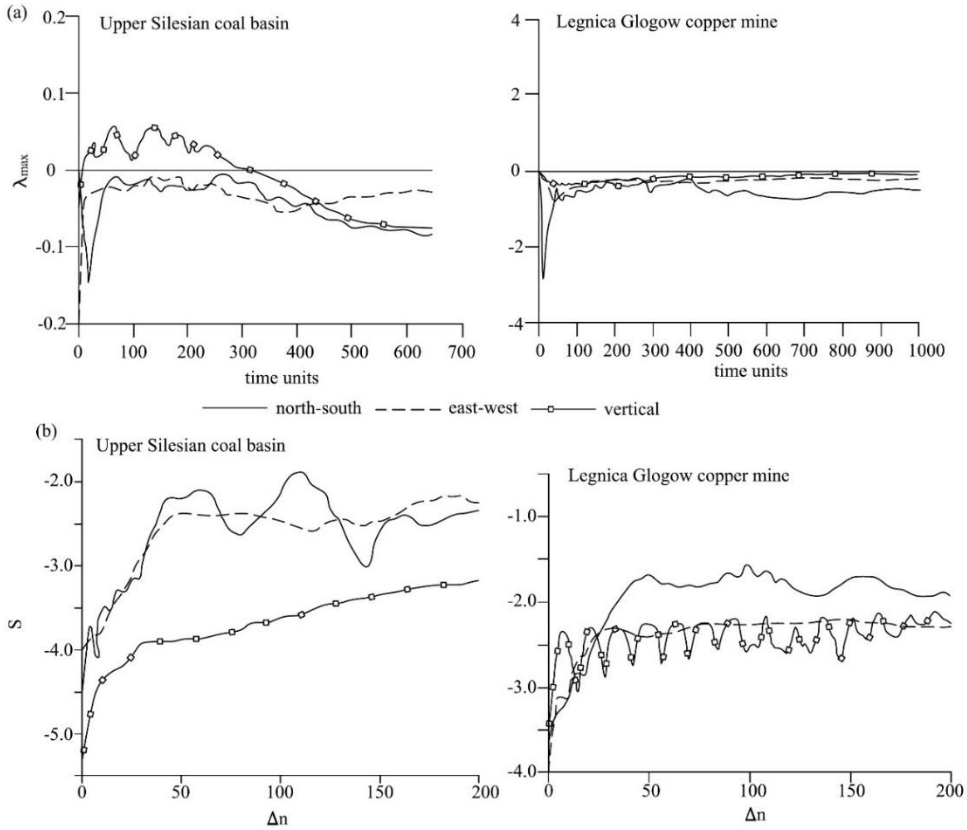

Figure 8 The largest Lyapunov exponent calculated according to Wolf's method (a) and Rosenstein method (b).

Based on the conducted research, one could derive general expression for estimation of mining-induced ground acceleration:

$$\dot{a} = Asin(\omega t) + Bcos(\omega t) - Ca(t) - a^3 + z(t)$$

$$dz(t) = -\frac{z}{\varepsilon}dt + \sqrt{\frac{2D}{\varepsilon}}dW \quad (1)$$

where A and B are Fourier coefficients, while parameter C controls the effect of autocorrelation properties on acceleration time history. Variable *a* stands for the mining-induced ground acceleration, while upper dot denotes the time derivative. Variable *z(t)* represents an Ornstein-Uhlenbeck process, and term $(2D/\varepsilon)^{1/2}dW$ represents stochastic increment of independent Wiener process. Colored noise generated by Ornstein-Uhlenbeck process with this parametrization is referred to as power-limited colored noise.

4 CONCLUSION

In present paper, we examined recorded ground acceleration induced by mining activities at two locations: Upper Silesian cola basin (M1.5) and Legnica Glogow copper mine (M2), both in Poland. Analysis was conducted for all three directions of acceleration: north-south, east-west and vertical. Aim of the analysis was to examine whether the recorded time series could be characterized as deterministic, stochastic, or they represent an example of deterministic chaos, to estimate the possibility of predicting the mining-induced oscillations. For this purpose, we applied a bundle of nonlinear time series analyzes, which resulted in following:

- we embedded the recorded time series into the appropriate phase space, by calculating the minimum embedding dimension and optimum embedding delay. Relatively high value of embedding dimension and the fact that the number of the nearest neighbors increase with the increase of embedding dimension could be treated as indications of strong stochasticity in the observed time series;
- none of the recorded ground series could be characterized as independent random numbers drawn from some fixed but unknown distribution;
- ground acceleration recorded in horizontal plane at Legnica Glogow copper mine could be characterized as stationary linear stochastic processes with Gaussian inputs
- ground acceleration recorded at Upper Silesian coal basin originates from a stationary Gaussian linear process that has been distorted by a monotonic, instantaneous, time-independent non-linear function
- ground acceleration in vertical direction recorded at Legnica Glogow copper mine could not be ascribed to any of the examined processes, probably due to high level of instrumental or background noise.
- All the examined time series are stationary (parameters of the system do not change in time), with all cross-prediction errors differing maximally by a factor of 2;
- Low determinism factor (0.7 and smaller) and negative maximum Lyapunov exponent, including the quick saturation of neighboring points distance with the increase of embedding dimension, indicate the absence of determinism in the recorded time series.

Results obtained indicate that ground acceleration time series induced by mining activities, for seismic events below M2, could not be reliably predicted. Instead, one needs to investigate the possibility of relating the peak ground acceleration and time series duration with the magnitude of seismic event. Also, it would be interesting to confirm the conclusions of this research for stronger seismic events (M>2).

REFERENCES

SMITH, R.B. et al. (1974) Source mechanisms of microearthquakes associated with underground mines in eastern Utah. *Bulletin of seismological Society of America* 64, pp.1295-1317.

WONG, I.G. (1985) Mining-induced earthquakes in the Book Cliffs and eastern Wasatch Plateau, Utah, USA. *International Journal of Rock Mechanics and Mining sciences, Geomechanical Abstracts*, 22, pp.263-270.

CUI, H., LI, H. and JIANG, F. (2004) Newborn natural gas resources in coal basin. *Journal of Jiaozuo Institute of Technology*, 23, pp.430-432.

DONNELLY, L. (2006) A review of coal mining induced fault reactivation in Great Britain. *Quaternary Journal of Engineering Geology and Hydrogeology*, 39, pp.5-50.

ZEMBATY, Z. (2011) How to model rockburst seismic loads for civil engineering purposes? *Bulletin of Earthquake Engineering*, 9, pp.1403-1416.

KOSTIĆ, S. (2013) *Nonlinear dynamical modeling of seismic events induced by stress change due to excavation of horizontal underground chambers*. PhD thesis, University of Belgrade - Faculty of Mining and Geology

GIBOWICZ, S.J. (1984) The mechanism of large mining tremors in Poland. In: Gay, N.C., Wainwright, E.H. (eds.) Rockbursts and seismicity in Mines, South African Institute of mining and metallurgy Symposium Series 6, 17-29.

ZOBACK, M. L. and ZOBACK, M.D. (1989) *Tectonic stress field of the continental United States*. Geophysical Framework of the Continental United States, L. C. Pakiser, Walter D. Mooney, Geological society of America, Memoir, 172, pp.523-539.

WETMILLER, R.J. et al. (1990) Investigation of natural and mining-related seismic activity in northern Ontario. In: *Fairhurst, C. (ed.) Proceedings of the 2nd International symposium of rockbursts and seismicity in mines, Rotterdam, 1990*. Rotterdam: Balkema Publishers, pp.29-37.

MILEV, A.M., SPOTTISWOODE, S.M. and NOBLE, K.R. (1995) Mine-induced seismicity at East Rand Proprietary Mines. *International Journal of Rock Mechanics and Mining Sciences*, 32(6), pp.629-632.

MCGARR, A., FLETCHER, J.B. (2005) Development of ground-motion prediction equations relevant to shallow-mining-induced seismicity in the Trial Mountain area, Emery County, Utah. *Bulletin of the Seismological Society of America*, 95(1), pp.31-47.

FRITSCHEN, R. (2010) Mining-induced seismicity in the Saarland, Germany. *Pure and Applied Geophysics*, 167(1-2), pp.77-89.

LIZUREK, G., RUDZIŃSKI, Ł., PLESIEWICZ, B. (2015) Mining induced seismic event on an inactive fault. *Acta Geophysica*, 63(1), pp.176-200.

EMANOV et al. (2021) Induced Seismicity of the Bachat Coal Mine and the Stress State of the Earth's Crust. *Journal of Volcanology and Seismology*, 15(6), pp.435-444.

KODBA, S., PERC, M., MARHL, M. (2005) Detecting chaos from a time series. *Eur. J. Phys.*, 26, pp.205–215.

KOSTIĆ, S. et al. (2013) Stochastic nature of earthquake ground motion. *Physica A: Statistical Mechanics and its Applications*, 392(18) pp. 4134-4145

DULINSKA, J.M. and FABIJANSKA, M. (2011) Large-dimensional shells under mining tremors from various mining regions in Poland. *World Academy of Science, Engineering and Technology International Journal of Civil and Environmental Engineering*, 5(11), pp.1443-1450.

PERC, A.K. et al. (2008) Establishing the stochastic nature of intracellular calcium oscillations from experimental data. *Biophys. Chem.*, 132, pp.33–38.

SCHREIBER, T. (1995) Efficient neighbor searching in nonlinear time series analysis. *International Journal of Bifurcation and Chaos*, 5, pp.349-358.

WOLF, A. et al. (1985) Determining Lyapunov exponents from a time series. *Physica D: Nonlinear Phenomena*, 16,(3) pp.285-317.

ROSENSTEIN, M.T., COLLINS, J.J. and DE LUCA, C.J. (1993) A practical method for calculating largest Lyapunov exponents from small data sets. *Physica D: Nonlinear Phenomena*, 65(1-2), pp.117-134.