10. Saadeldin, R., Gamal, H., Elkatatny, S., Abdulraheem, A. (2021). Intelligent Model for Predicting Downhole Vibrations Using Surface Drilling Data During Horizontal Drilling. *Journal of Energy Resources Technology, 144 (8)*. doi: https://doi.org/10.1115/1.4052794

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IMPROVEMENT OF THE METHODOLOGY FOR PREDICTING GAS-DYNAMIC PHENOMENA ON THE BASIS OF MODERN SOUND-CAPTURING EQUIPMENT

The object of the study is the sound accompaniment of the processes of stress redistribution in the bottom part of the coal seam, which precede the release of rock, coal, and gas. Among the hazards of underground coal mining, gas-dynamic phenomena (GDP) are the most complex in nature and the most dangerous in terms of consequences of high dynamic power and the release of a large amount of mechanical energy in the form of fractures and gas in a short period of time. This leads to accidents due to sudden gassing and blockages of workings with coal and rock, as well as explosions of methane and coal dust, destruction of the workings' support, damage to machinery and mechanisms, equipment, and devices. The greatest hazard among GDPs is posed by sudden releases of coal and gas, rock and gas, gas releases with destruction of host rocks and with destruction of the ground of the workings, as well as gas breakthroughs from tectonic fault zones.

Therefore, the accuracy of predicting possible gas-dynamic phenomena significantly affects the level of safety of miners. The acoustic emission (AE) method is used to predict the gas-dynamic activity of a rock massif. The analysis of acoustic emission studies based on archival data in coal seams subject to gas-dynamic activity has made it possible to substantiate the possibility of improving the accuracy of the forecast of emission hazard, which has a social and economic effect. On the basis of exploratory research and production tests, the software for automated calculations of the GDP forecast was improved and an improved Methodology for forecasting gas-dynamic phenomena based on modern sound-capturing equipment was developed. A scientific justification for the reference interval of AE observations in the conditions of a particular longwall was developed.

The developed software and the forecasting methodology were tested in the conditions of the Tsentralna mine of the Toretskugol State Enterprise (Toretsk, Donetsk region, Ukraine). The practical significance of the work is that a method for predicting explosion hazard has been developed, taking into account the modern capabilities of equipment and methods of input data processing, which allows to increase the productivity of mining and tunneling operations in coal seams without reducing the safety of miners.

Keywords: *gas-dynamic phenomena, acoustic emission, signs of gas-dynamic activity zones, manifestations of mining pressure, prediction of GDP.*

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1. Introduction

The efficiency and safety of mining operations largely depend on the nature of the manifestation of mining pressure, which is one of the most significant phenomena associated with the development of coal deposits, so many studies have been devoted to it and many methods have been proposed to predict areas of high mining pressure.

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Among the existing methods for predicting dangerous manifestations of mining pressure, geophysical methods, namely seismic and acoustic methods of forecasting, have become widespread [1–3].

The rocks in a virgin rock mass are in a state of stress equilibrium. During mining operations, the equilibrium in the massif is disturbed and stress redistribution occurs. Under the influence of mining operations in the massif, there is a constant process of stress redistribution in the marginal area of these operations. The redistribution of stress is accompanied by the formation of local discontinuities and the generation of sound waves in a wide frequency range (the phenomenon of acoustic emission).

An increase in the total stress in the bottomhole part of the array leads to an increase in the number of pulses recorded per unit of time, and unevenness in the redistribution of stress is manifested in the unevenness of the recorded number of pulses in neighboring reference intervals.

Thus, regular observations of the seismic and acoustic regime of the coal seam edge allow monitoring relative changes in the nature of stress redistribution in the coal massif and the associated threats of gas-dynamic activity in the mining area.

Changes in the seismic-acoustic indicator of rock pressure manifestation allow to consider the possibility of solving the problem of objective assessment of the optimality of the adopted method of rock pressure control in specific mining and geological conditions, as well as forecasting changes in rock pressure manifestation based on the results of its current assessment.

At the same time, a large list of situations that lead to increased mining pressure and a complex stress state of the rock mass indicates the scope of possible problems that arise when trying to assess these stresses. Especially in the conditions of an operating mining enterprise, whose working faces are constantly moving in the space of the rock massif and constantly require reasonable conclusions about the geomechanical state in the environment, preferably without significant interference with the mining process. In general terms, the problem of assessing the complex stress state of a rock mass has not been solved to date. There are also no systems for monitoring the stresses in place in the rock mass surrounding the face of a preparatory or treatment workings.

The only exceptions are systems for monitoring caused acoustic emission (AE). The reason for this is the very nature of acoustic emission. Discontinuities in the rock mass continuity accompanied by AE occur where local stresses exceed the local tensile strength. Without answering the question about the absolute value of the stress, the method of induced AE naturally reports the presence of abnormally high stresses for a particular massif, the concentration of stress centers, the dynamics of fracture in the fracture centers, and so on.

By observing the caused AE, it is possible to integrally assess the compliance of the mining technology used with regard to the possible mining pressure forces and the current geomechanical situation and then link it to the source of the increased stress based on the analysis of additional information.

Another important feature of the induced AE method has been repeatedly noted: minimal interference with mining operations. The AE method has been used in Donbass mines for over forty years. During this time, the mining and geological and mining engineering conditions have changed significantly, which requires adjustments to the relevant guidelines for applying the method. On the other hand, there have been significant changes in the radio engineering devices used for AE observations and in the means of processing the incoming information, which allow for the implementation of labor-intensive algorithms for efficient data processing.

Despite the large volume of successful use of the induced AE method, the method has not been resolved all this time. To date, the length of hazardous zones has not been empirically substantiated, and there is no methodology for adjusting the forecast parameters.

Therefore, when forecasting by the method of induced acoustic emission, the most commonly used method is the method of forecast calculations based on the analysis of the results of acoustic emission observations organized into time series [4]. When reviewing the possible directions of AE time series analysis, it is possible to refer to such mathematical sections as fractal analysis, wavelet analysis, and the theory of dynamic chaos. These disciplines have recently gained great importance in the analysis of complex and complex data [5–8]. An adequate mathematical toolkit has been invented for modeling processes, namely the theory of fractals [9]. The modern view of the problem of describing real processes in most of the AE events around us has revealed the fundamental feature of these processes – their fractal nature. In practice, this has the following meaning: the mathematical relationships between the quantities obtained from experiments and their functions should be described by formulas with a fractional degree indicator. This is how the practical significance of the results increases.

The forecasting methodology based on the analysis of the results of acoustic emission observations organized in time series has been applied in the sound-catching equipment ZUA-98 (Ukraine), which is used in Ukrainian mines. Given the technical capabilities of the ZUA-98 equipment, with the start of its operation, extraordinary opportunities have opened up for improving methods for predicting the hazard of coal and gas emissions based on the caused acoustic emission, but to date, these opportunities have not been fully utilized.

Accordingly, *the aim of the research* is to provide a reliable forecast of gas-dynamic phenomena, improve safety in mines prone to gas-dynamic phenomena (GDP), and increase the efficiency of coal mines that mine coal seams prone to GDP.

2. Materials and Methods

The AE time series is one of the types of processes occurring in nature and technology that have a fractal nature. When studying such processes, it is necessary to study their fractal features (to measure the scaling parameters) and optimize the procedure for measuring the parameters of the AE time series based on the specific features of the process. An operating coal mining enterprise should be attributed to the facilities where conducting experiments is maximally complicated by the complexity of the technological process. As a consequence of this circumstance, time series of observations contain not only useful information about the state of the rock mass, but also a large number of obstacles that have an undeniable impact on forecasting and which it is necessary to deal with when making predictions. The main working idea of our study was the following: the fractal properties of the AE time series for regular changes in observations and random components of the same series do not coincide and therefore will reduce the impact of interference on the forecasting result.

In these studies, the methodology proposed by Hurst [10, 11] was applied for the first time in the coal industry to study the scaling of AE time series. This methodology is supposed to determine the scaling parameters for a particular face and use its numerical value to optimize the forecasts in a particular face. For this purpose, an experimental version of the program specialized in measuring the fractal parameters of the AE time series according to the Hurst method (hereinafter referred to as the «Persistence» software) was developed.

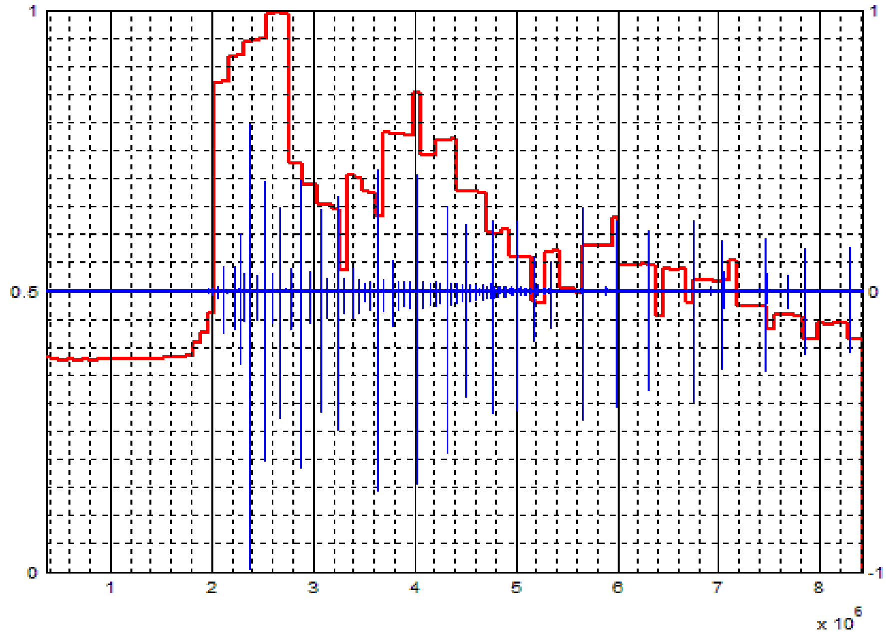

Fig. 1. Study of the persistence of the electrical signal AE accompanying the collapse of the roof in the lava. The analysis interval is 725000 samples. The electrical signal is blue, the Hurst indicator is red

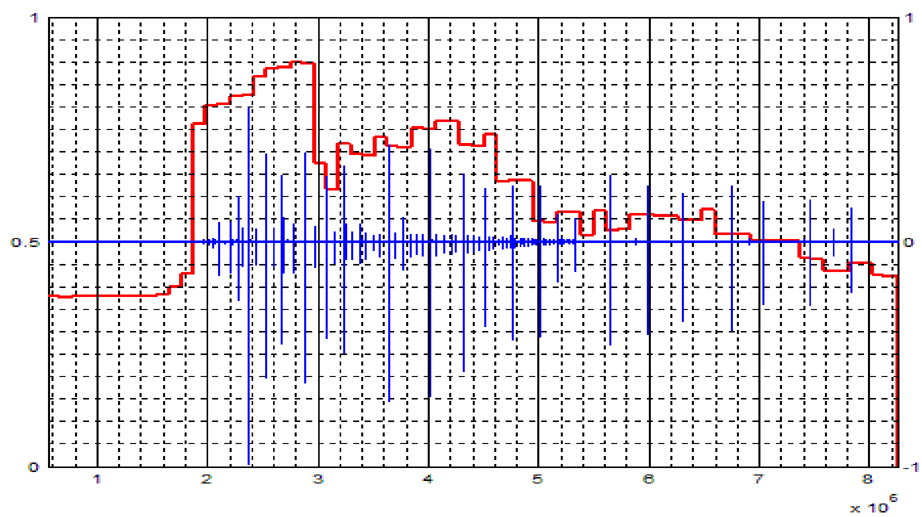

Fig. 2. Study of persistence for the electrical signal AE accompanying the collapse of the roof in the lava. The analysis interval is 1000000 samples. The electrical signal is blue, the Hurst index is red

3. Result and Discussion

The fractal properties of the audio recording in the 8th western longwall of the Hlyboka mine, which includes recorded AE pulses of three large-scale fracture levels without any interference, were studied using the ZUA-98 sound-capturing equipment. These data are presented in the form of a wav-file with a sampling frequency of *Fs*=11025 Hz and the number of bits=16 per sample. Several results of the program execution with a variable value of the window length were analyzed.

The graphical results of the program are shown in Fig. 1, 2.

The graphs in Fig. 1, 2, it can be seen that the Hurst exponent indicates a close connection of events at all scale levels and has clearly expressed spikes at those moments of time when the highest energy AE pulses are registered. In addition, these images show the effect of the length of the sampling interval (dive depth) on the value of the Hurst index. When the window is increased, the Hurst index initially increases slowly, but at too large window lengths, the Hurst index graph shifts or blurs relative to individual acoustic emission events. It was found that at a window length of 2500000 samples or more, the Hurst parameter partially loses its informativeness. It may also be promising to study the behavior of the Hurst exponent at shallow immersion depths, but such a study is associated with the need for a radical change in the software.

In the future, the main tool for conducting the research was a retrospective analysis of acoustic emission time series using the developed computer program for processing AE time series and experimental substantiation of additional signs of gas-dynamic activity hazard.

The peculiarity of this program is the processing of time series with the estimation of the Hurst's index by the *R/S analysis method* with some changes, namely: searching for a time series segment where it is advisable to calculate the correlation between *log(R/S)* and *logN* with the possibility of a detailed view of this dependence in order to determine its breakpoints at certain *N*. It is with those points that the attractors of the time series are associated, i. e., those periods of AE observations in which the greatest correspondence of processing and informativeness of the time series should be expected. From the previous considerations, it is clear that too large segments of observations do not make practical sense precisely because of the need for a long set of these data without the ability to calculate the forecast of the state of the face. In addition, the so-called «lag theorem», known from higher mathematics, states that a long data set leads to diagnostic decisions being made at a time when the practical value of those decisions is exhausted. Too short preliminary observations are also meaningless because they do not generate sufficient statistics. In general, the justification of the reference interval of observations in the conditions of a particular mine face is a classic example of the problem of optimization between the desired and the practically achievable.

The fractal nature of the rock mass displacement process, which is forged by mining operations, is easily detected during long-term AE observations. Thus, it is necessary to assume the presence of a large number of attractors in the dependence between *log(R/S)* and *logN, which* correspond to the steps of subsidence of the overburden – firstly, this is true. Secondly, when introducing this method of analysis, it is necessary to be aware that the complex structure of the time series will «entail» the dependence of all the results of the *R/S analysis on a* random initial reading of the AE time series. Thirdly, and most importantly, the forecast of gas-dynamic manifestations is associated with short, maximally prompt observations and the detection of anomalous data at these conditionally «short» observation intervals.

The following was used to justify such «short» intervals. Archival AE observations are in the form of continuous time series of several thousand ten-minute AE samples. From these series, a large number of time series segments of 500 samples were «sliced» using the Monte Carlo method, and the beginnings of those segments were placed statistically independently throughout the time series. As a result, statistically valid volumes of observations were accumulated to find the optimal resistance intervals.

Subsequently, the fractal features of time series were studied in the 29th Orlovska longwall by observations lasting about 1 month. During this time, the face moved by about 90–100 meters, i. e., the time series should contain information about several subsidence of the immediate and main roof. The AE time series, built according to the standard methodology, is shown in Fig. 3.

Visually in Fig. 3, several anomalies in the AE activity can be distinguished, including a long anomaly, which should obviously be associated with the influence of the Samsonivskyi thrust. Thus, it is expected that a preliminary analysis of the fractal features of this time series should provide initial information for optimizing the processing of the time series as a whole.

To do this, the Persistence function was used to study the dependence of the persistence of the time series on the length of the interval of aggregation of the initial data, which is shown in Fig. 4.

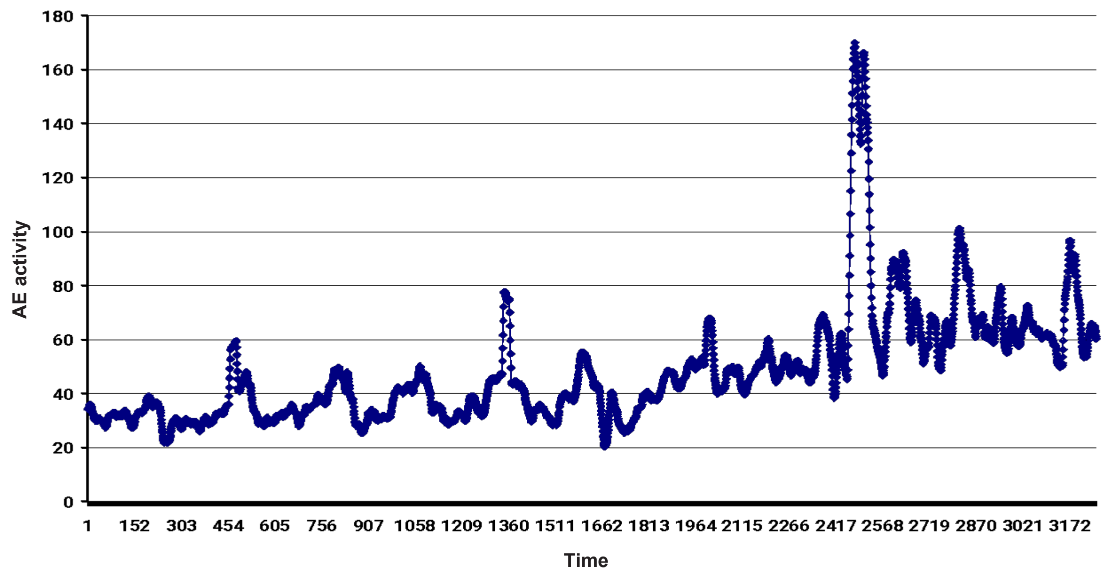

Fig. 3. Initial time series of AE

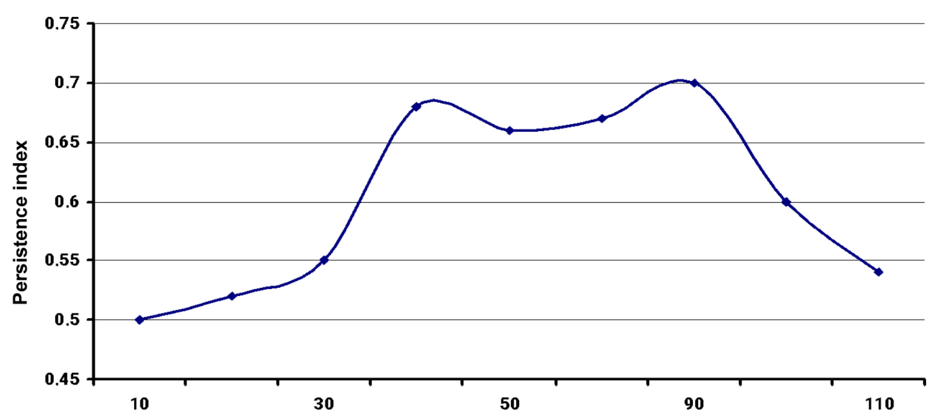

Fig. 4. Dependence of the persistence index on the length of the «elementary» observation interval

The analysis of the data shows that the optimal intervals for averaging the initial data lie in the range of values from about 40 to 80 minutes. Given that an increase in the averaging interval increases the inertia of the forecast, i. e., along with the increase in the predictive capabilities of the initial data, the delay time of the forecast in relation to the actual process increases with the increase in the aggregation interval, it is possible to set the first constant of the initial data processing time (the length of the «elementary» observation interval) equal to 40 minutes. Such a choice of the «elementary» observation interval allows to count on sufficient information content of the initial data while maintaining the required promptness of forecasts.

According to Fig. 4, the persistence index changes the slope angle at time intervals of about 4.5 hours, as well as 15 hours, 25 hours, and 37 hours. Thus, the analysis of the persistence of the initial AE time series provides parameters for filtering the data received by the averaging method in the time domain or frequency domain when using the Fourier transform.

Below is an example of filtering in the time domain. To do this, the original data was averaged (Fig. 3), sequentially first with a constant rolling averaging interval of 40 minutes, and then with a constant averaging interval of 15 hours. The result shown in Fig. 5 is very «transparent» (free from unnecessary details), despite the averaging interval being half as long as the one used in the regulatory guidelines.

As a result, the following can be noted:

1. The methodology used to calculate the forecast is optimized only for simplicity of calculations and may not be optimal in specific conditions.

2. Analyzing the intervals in which the AE time series has maximum persistence allows to optimize the forecast algorithm. But the above does not exhaust the possibilities of fractal analysis.

To deepen the description of the methods and capabilities of fractal analysis, it is also important to note that forecasting as such is based on such a natural phenomenon as the memory of natural processes.

At the scientific and technical level, the concept of long-term memory is a property that describes the high-order correlation structure of a time series. If a series has a long memory, then there is a relationship between observations that are more or less far apart in time. Long-memory processes were first developed by Hurst [10, 11] when studying the tributaries of the Nile. The basis of the analysis is the calculation of the self-similarity parameter (*Hurst*, *H*).

The Hurst exponent allows to calculate the fractal dimension and is thus a tool for fractal analysis. In addition, this indicator can be used to distinguish a random series from a nonrandom series, even if the random series is not normally distributed.

The methodology for calculating the Hurst parameter is proposed to be used to plot the change in the *H* parameter throughout the entire series under study. Thus, it is possible to observe the trend in the change of the *H parameter and draw* appropriate conclusions. To implement this algorithm, a fixed-size sliding window was used. Thus, the obtained data set allows to build and visually evaluate the change in the self-similarity parameter *H*. It should be noted that the value of the length of the sliding window also affects the result. This is determined by how much data with a long-term dependence is concentrated within the window. At the same time, if the value of the window length is close to the length of the series, it is not possible to get reliable results – an average value will be obtained, which can «hide» the outbursts of the *H* parameter. Using a software package developed for analyzing fractal features of time series, the time series of AEs were studied. The purpose of the search was to substantiate the parameters of the improved forecast, namely:

– the smallest, «elementary» observation interval at which it is advisable to form an alphabet of AE observation results and build AE time series;
– the resistive interval of the AE time series, where it is possible to effectively calculate the forecast of the state of the bottom part of the coal seam;
– the forecast horizon, i. e. the time interval for which the forecast conclusion applies;
– criteria for entering and exiting the «dangerous» and «safe» states.

Each dependence between *log(R/S)* and *logN* was automatically analyzed to find the points of location of local extrema *of log(R/S)* relative to the *logN* axis, i. e., the attractors of the time series. The statistics of the locations of local extrema *of log(R/S)* relative to the *logN* axis were automatically generated in the form of a table of raw data and their histogram, an example is shown in Fig. 6.

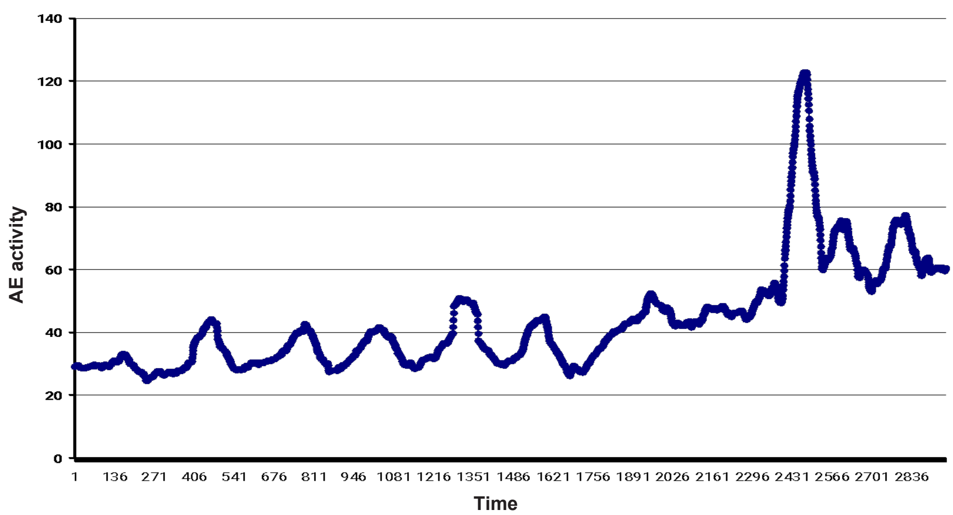

Fig. 5. AE time series with double time filtering

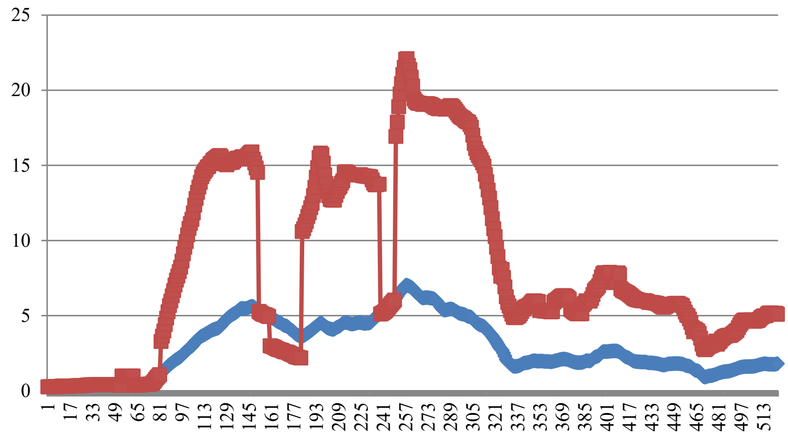

Fig. 6. Comparison of the original (blue graph) and corrected (red graph) AE time series

The conclusions from the statistics of the *R/S* correlation results were as follows:

a) attractors corresponding to the fastest processes of stress redistribution in the bottomhole lie in the range of values from 3–4 hours to 10–15 hours. The mathematical expectation is about 8 hours. In other words, these attractors reflect the effect of modulation of the processes of convergence of side rocks by the technological cycle of the mine, which is known from the forecasting practice. Comparison of the attractors for a steeply dipping mine and a mechanized face of a gently sloping mine also yields a physically understandable result: convergence processes are slower in a steeply dipping mine. A comparison of the attractors for the top and bottom of the same face shows that attractors occur more frequently in the top. This is a well-known phenomenon in geomechanics for longwall faces that produce coal in panels along the strike: in the upper parts of such faces, the roof pitch is shorter than in the lower parts;

b) within the same registration path, the most probable values are expressed with a scatter, which confirms the influence of random factors;

c) for modern mechanized workings, it is necessary to reduce the averaging intervals compared to the daily intervals used by the existing methodology for calculating the forecast. The averaging intervals should be reduced to half a day or to the duration of a shift. In the current (in the sense of continuous) calculation of forecasts, it is possible to limit to a half-day duration. To make the final choice, analyze the first Hurst coefficient for observations in the conditions of a particular production site;

d) the forecasting horizon should be estimated as part of the value of the duration of fast attractors in the conditions of a particular AE observation path. It is most likely that the forecasting horizons for the «safe» and «dangerous» states have different values. Perhaps, within the framework of long observations at a particular facility, the forecasting horizon may depend on the components of the shift process of higher orders, i. e., have a dynamic character.

After analyzing the table of dependencies between *log(R/S)* and *logN* in the conditions of a particular reservoir, the time series of AE was analyzed by the Hurst method using a moving interval on the segments of *N* values that covered approximately 80–90 % of the local extremes identified in the previous step. Thus, the AE time series was divided into persistent, statistically independent, and anti-persistent segments of observations.

The results of the research showed that:

1. The fractal analysis of the AE time series and the calculation of these series by the Hurst method have a physical content consistent with the practical experience of coal field development, but in essence they are formal computational procedures for identifying hidden patterns contained in the AE time series, which is studied in short segments in the current time.

2. Fractal analysis of the AE time series and calculation of these series by the Hurst method allow to identify time series parameters that are useful from a practical point of view, namely:

– to justify the appropriate intervals for processing observation results, which should increase the efficiency and accuracy of forecast calculations;

– to introduce formal criteria for distinguishing between stochastic and persistent components of the cracking process in the rock mass surrounding the mining site;

– to develop a procedure for assessing the forecast horizon of conclusions about the condition of the face.

The time series of AEs with markings for persistent segments of observations can be adjusted for the value of persistence. Thus, let's introduce a procedure for formally dividing the total set of input data into those that have signs of safety and danger.

On the basis of the performed studies, the software and the improved Methodology for GDE forecasting were developed, which is based on the phenomenon of generation of acoustic emission pulses accompanying plastic deformations in the rock mass. The main difference of the improved Forecasting Methodology is the continuous study of the persistent properties of the predicted acoustic emission (AE) graph (AE time series). The improved Methodology allows to improve the forecast calculations based on new methods of information processing using Hurst statistics. The new forecasting capabilities are achieved by computer processing of the obtained data using the original calculation methods for the coal industry.

The results of the laboratory studies show the following new features of the forecast:

– the ability to substantiate the parameters of observations and forecast calculations in the conditions of a particular face;

– the ability to set a «safe» forecast horizon in the conditions of a particular wellbore, i. e., to determine the time period for making technically sound decisions to combat threats;

– the ability to reduce the length of potentially hazardous areas without compromising miner safety;

– the data of acoustic emission observations are entered into a computer by forecast operators. This data is processed fully automatically in real time, with the forecast results calculated every 10 minutes and the technical staff notified of the array status. If necessary, such a system can be connected to a high-level information system.

The developed improved Methodology for predicting gas-dynamic phenomena based on modern sound-collecting equipment, an expanded information base and new methods for processing acoustic emission data has been successfully tested in the conditions of the mine «Central» SE «Toretskugol» (Toretsk, Donetsk region, Ukraine), according to the order of SE «Toretskugol» dated 13.05.2019 No. 6.

The only limitations to the use of the new Methodology may be the lack of ZUA-98 equipment at the mining enterprise, as well as the impact of martial law conditions, which result in the destruction of mines and shutdown of their operations.

The practical significance of the research is that the developed method for predicting the emission hazard, taking into account the modern capabilities of the equipment and the methodology for processing incoming data, allows to increase the productivity of mining and sinking operations in coal seams without reducing the safety of miners.

The prospect of further research is to connect the developed forecasting system to the information system of occupational health and safety management based on risk management.

4. Conclusions

The developed improved Methodology by the method of induced AE implements a formal calculation algorithm without the participation of the forecast operator. The proposed calculation algorithm is more efficient than the one currently used. Analysis of the AE time series using the tools of the Expert Workstation allows optimizing the parameters of the forecast calculation in the conditions of a particular face. The difference between the improved Methodology and the existing ones is the use of a formal mathematical apparatus that can justify the parameters of forecast calculations in specific conditions.

Production tests have confirmed the effectiveness of the improved Methodology for GDN prediction based on new methods of acoustic emission data processing, which allows:

– justify the parameters of observations and forecast calculations in the conditions of a particular face;
– set the «safe» forecast horizon in the conditions of a particular mine, i. e., determine the time period for making technically sound decisions to combat threats;
– allows the forecast operator to enter observation data into the computer, which is processed fully automatically and notifies the technical staff of the forecast results;
– if necessary, such a system can be connected to a high-level information system.

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Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or other, that could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the presented work.

References

1. Ettinger, I. L. (1969). *Vnezapnye vybrosy uglia i gaza i struktura uglia*. Nedra, 160.
2. He, M., Wang, Q. (2023). Rock dynamics in deep mining. *International Journal of Mining Science and Technology, 33 (9),* 1065–1082. doi: https://doi.org/10.1016/j.ijmst.2023.07.006
3. Feng, X. T., Chen, B. G., Ming, H. J., Wu, S. Y., Xiao, Y. X., Feng, G. L. et al. (2012). Evolution law and mechanism of rockbursts in deep tunnels: Immediate rockburst. *Chinese Journal of Rock Mechanics and Engineering, 31 (3),* 433–444.
4. Antciferov, M. S., Konstantinova, A. G., Pereverzev, L. B. (1960). *Seismoakusticheskie issledovaniia v ugolnykh shakhtakh*. Izd-vo AK Nauk Ukrainy, 103.
5. Zhang, J., Wang, M., Zhou, H., Zhang, D., Yu, B., Wang, C., Wang, Y. (2023). Coal and rock dynamic disaster prevention and control technology in the large mining face of a deep outburst mine. *Frontiers of Earth Science, 17 (3),* 701–712. doi: https://doi.org/10.1007/s11707-022-1060-8
6. Li, C. C., Mikula, P., Simser, B., Hebblewhite, B., Joughin, W., Feng, X., Xu, N. (2019). Discussions on rockburst and dynamic ground support in deep mines. *Journal of Rock Mechanics and Geotechnical Engineering, 11 (5),* 1110–1118. doi: https://doi.org/10.1016/j.jrmge.2019.06.001
7. Baranov, V., Antipovich, Y., Stefanko, S. (2023). Frictional phenomena in coal mines: reasons, consequences and influence on gas dynamic and thermal phenomena. *Visnyk of Taras Shevchenko National University of Kyiv. Geology, 3 (102),* 5–9. doi: https://doi.org/10.17721/1728-2713.102.01
8. Baranov, V. A., Pashchenko, P. S., Stefanko, S. V. (2023). Forecast of tectonic disturbances zones in coal layers. *Geofizicheskiy Zhurnal, 44 (5),* 123–133. doi: https://doi.org/10.24028/gj.v44i5.272332
9. Balkhanov, V. K. (2013). *Osnovy fraktalnoi geometrii i fraktalnogo ischisleniia*. Izdatelstvo BGU, 224.
10. Hurst, H. E. (1951). Long-term storage capacity of reservoirs. *Transactions of American Society of Civil Engineers, 116,* 770–799.
11. Hurst, H. E., Black, R. P., Simaika, Y. M. (1965). *Long-term storage: an experimental study*. Constable. London.

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