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DATA ANALYSIS SOLUTIONS TO IMPROVE BLASTING EFFICIENCY IN MINING

Purpose. To build an identification model to determine the appropriate explosion parameters value with reasonable cost. To optimize blasting works design at each blast site with the calculation of delay time based on the model used.

Methodology. Blasting for mining is an issue of utilizing the most of explosive energy in order to achieve the highest smashing ability and the smallest level of vibration. In modern explosive techniques, the total amount of explosive is divided into parts to detonate after differential time intervals. This solution creates interference between stress waves causing the durability of rock structures to be reduced and the blasting efficiency to be improved. Although delay time plays an important role in this method, so far its value is still calculated empirically at the blast site due to the irregular characteristic of the rock environment. Technical design parameters for explosion including delay time has been also determined from smart analysis software and simulation models. However, their applicability is limited because of high payments and strict implementation conditions. The method proposed in the study overcomes this drawback and its effectiveness is proven by the process of analyzing experimental data at Nui Beo Mountain of Vietnam.

Findings. An identification model is developed based on the information including: explosion delay time value; average propagation speed of the vibration wave; maximum amplitude of the vibration wave.

Originality. Basic data analysis software and an artificial neural network model are used. A new data analysis algorithm is established to determine the optimal explosion delay time value.

Practical value. A simple and reasonable-cost solution is formed for improving the efficiency of blasting in mining.

Keywords: *blasting mining, identification model, data analysis*

Introduction. ***Overview.*** *Compression wave and vibration wave.* When an amount of explosive is detonated, the explosive energy creates a compression wave that causes pressure to break the rock and soil around the explosion point. The compression wave spreads around and gradually reduces the energy due to loss in rock breaking. When the wave energy drops below the breaking level and is only capable of creating rock vibrations, the compression wave is called a vibration wave [1]. If the energy loss is considered insignificant, the explosive energy is the sum of the compression wave energy and vibration wave energy. The compression wave has a short duration and a very short propagation distance, located in the dangerous area of the blasting site. Therefore, waves cannot be studied directly. The breaking capacity of a compression wave is often calculated indirectly through parameters such as vibration level and wave propagation velocity.

The vibration level is the oscillation velocity of rock particles around the equilibrium position when a wave passes through. It depends on the distance from the measuring point to the explosion point and the amount of explosive used in one blast. The longer the measuring distance and the smaller the amount of explosives, the lower the vibration. The amplitude of vibration rock particles is the amplitude of the vibration wave.

Wave propagation velocity represents the speed at which vibration wave moves from the explosion point to the measurement point on the earth's crust. Its speed ranges from about 305–6100 m/s depending on the area. In a certain area, this value is almost constant [1, 2]. For this reason, creating a time delay after each explosions causes the vibration wave between explosions to propagate slowly after a corresponding period of time. The propagation speed is large, while the distance from one explosion point to other is small, so the wave peaks propagate and never meet each other (Fig. 1). Therefore, they are separated and the level of vibration only depends on the amount of explosives at one time and not on the amount of explosives in the whole yard [1].

The energy emitted from the explosion point travels in all directions with equal value in a homogeneous medium. Then, the vibration level in all directions will be equal. However, vibration transmission is not ideal in reality because changes in the earth's structure, geological structure, cracks, ... will change the level and frequency of vibrations.

Components of vibration wave. The vibration waves include three components: compression wave – *P*; shear wave – *S* and Rayleigh – *R* wave. Among them, the one that brings the highest efficiency in breaking rock and also causes the most damage is the *P* wave. *P* spreads horizontally, straight from the explosion point to the measurement point. According to the LVT coordinate system (Fig. 1), the *L* axis represents the *P* wave component. The propagation velocity of the *P* wave (V_P) is the largest [2], in some cases $V_P \approx 2V_S$ (V_S is the propagation speed of the shear wave).

In the field of geophysics, when monitoring and surveying engineering geology, geophysicists are almost only interested in *P* waves to determine the state parameters of the rocky environment [2].

The value of V_P depends on many factors and properties of the rocky environment through which it is transmitted, such as: density of soil and rock; compression resistance; degree of cracking; direction of cracking; the degree of layering of the rock mass, the degree of hydration. These parameters have a close relationship, mutual influence making the V_P change according to a non-linear and non-repeating rule in different geological areas. Exploration and survey works are carried out regularly and continuously over a long period of time to determine the characteristics of geological changes for a certain field. These characteristics all show the changing trends of V_P according to parameters, typically as [2]:

- inverse proportional to soil moisture;
- proportional to density γ and density ρ;
- proportional to compression resistance σ;
- inverse proportional to the porosity of the rock;

and many other factors [2].

Effect of delay time on vibration level and breaking efficiency. The total amount of explosive is divided into parts to explode sequentially after appropriate time delays. This solution creates new free faces during blasting, which reduces structural strength. Besides, when there are many explosions in a blast, it will create the phenomenon of rocks flying and colliding with each other, increasing the possibility of breaking.

As the total amount of explosives per delay blasting time decreases, the vibration level decreases. If the number of explosive parts increases, the number of delay times will be correspondingly larger, leading to the magnitude of the vibration decreases.

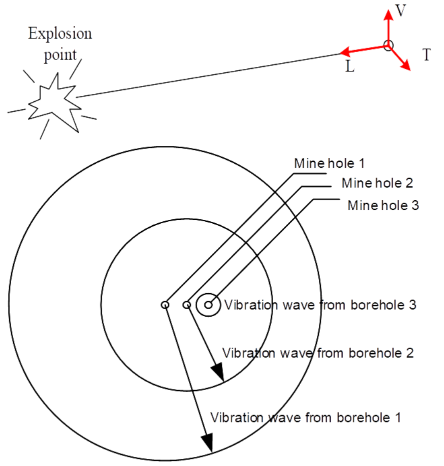


Fig. 1. Vibration wave propagation in delay blasting and LVT coordinate system

There are many random and irregular factors in natural rock environment. So, theoretical formulas are difficult to match practice. Furthermore, delay time proposed by inconsistent points of view makes it difficult to be applied. Currently, delay times are defined from the experimental lookup tables experiments and they are adjusted to suit the respective explosion conditions in each area (Table 1).

The simplest experimental formula for determining delay time (ms) is as follows

$$t = k \cdot R,$$

where k is the coefficient depending on the properties of rock (ms/m), for very hard rock $k = 3$, hard rock $k = 4$, medium hard rock $k = 5$, soft cracked rock $k = 6$. k is also called a background coefficient. R is burden (m).

For each type of rock with a certain hardness range, the delay time value corresponding to the magnitude of the burden will be determined (Table 1).

Research on delay blasting. The delay blasting method is based on the properties of compression wave propagation at short distances. Laboratory-scale tests of Rossmanith indicate that the interaction of compression waves and subsequent cracks can be used to increase the degree of rupture. To produce an interference effect, the delay time must be significantly shorter than usual. However, due to natural rock fractures, the delay time need to be selected based on the specific characteristics of the rock at the blast site. This information is not precisely defined for each explosion, so it is difficult to design an explosion with an interactive target. That is also the main reason for not being able to model explosions using mechanical calculation methods [4].

The compression wave propagating in the rock mass consists of two parts: longitudinal wave P and shear wave S. Each wave has the first half period of compression and the second half period of tensile. In the area near the explosion point, these two waves overlap; when spreading outward, they separate because the speed of the P wave is greater than that of the S wave. With the two holes spaced apart, the fundamental interaction of the compression waves from the two holes is: P1-P2, S1-S2, P1-S2, P2-S1. Interactions can occur many times when suitable explosives are used, creating compression fluctuations over a considerable period of time. The compression and deformation fields due to the minehole depend on the wave speed in the rock mass [5].

Table 1

Delay time for multi-row explosion [3]

Type of soil	Stiffness f	Delay time (ms) according to burden R (m)				
		1.5–3	3–4.5	4.5–6	6–8	8–10
Hard and very hard	12–20	12–15	19–21	25–31	31–37	37–44
Medium hardness	8–14	19–21	25–31	31–37	37–40	43–50
Sticky and soft	4–8	25–31	31–37	37–40	43–50	50–65

Katsabanis, et al. performed tests on 92 × 36 × 21 cm rock blocks in the laboratory. Hole distance is 10.2 cm, hole diameter 11 mm, hole depth 18 cm. The experimental time delay varied in the range 0–4000 microseconds. In another case study, 60 × 40 × 25 cm stone blocks are used [6]. Drill holes are 12 mm in diameter, 23 cm deep, and 10.5 cm apart. Delay time is tested from 100 microseconds or more. The results show that the degree of smashing decreases in case of simultaneous explosion (delay time is zero), the degree of breaking increases gradually as the delay time increases. There is little change as the delay time increases from 10 microseconds to 1 ms. The broken rock becomes larger when the delay time is long due to the fact that the rocks are stably separated by cracks [6, 7]. The optimal smashing level is achieved when the “differential time/ burden” ratio is between 4 and 10 ms/m.

Sjoberg [8] used simulation methods and computational tools to test Rossmanith’s hypothesis on a model with a hole diameter of 311 mm, a column height of 8 and 11 m with delay times, amount of explosives and hole distances changed. A small effect created from the compression wave interaction, but it was local and did not significantly improve the degree of rupture. The test also gave the result that, with a long enough delay time when the compression wave has passed through the second hole leading to the most degree of breaking.

Johansson and Ouchterlony [9] used laboratory prototypes to study the way in which short delays generate vibration wave interactions for the purpose of improving the degree of smashing. The model has 2 rows, each row has 5 holes 10 mm deep, the distance between rows is 110 mm. The measured P-wave velocity is 3800 m/s, the time for the wave to propagate to the neighboring hole is about 28 microseconds. The experimental delay time range ranges from the time value that the P wave has not yet reached the adjacent hole to the time value that the S wave has passed through the adjacent hole, corresponding to the range of 0–146 microseconds. They found that the second row of holes had a significantly different and more uniform degree of rupture than the first row, because of the reverse penetration of cracks from the first row. This shows that the previous compression in the rock mass plays an important role in changing the degree of crushing when performing a subsequent detonation.

Johnson [10] studied the effect of shock wave impact in rock mass and in explosive columns. The experiments were carried out on small concrete blocks, divided into three groups, using 50 gr/ft bursting wires. In the first test, the explosive wire passed through the center of the block and detonated from one end of the concrete block to avoid wave collisions. In the second test, the explosive wire still penetrated the center of the block but was detonated at both ends to create a blast wave impact through the center of the concrete block. The third test had no explosives at the center of the rock, but only at the ends. Detonate both ends to create a vibration wave that travels through the concrete block and collides in the center of the block. Simultaneous detonation and delay time explosion are both performed. This test is similar to what happens between explosion holes in real life. The results showed that the second test created a radial crack similar to the first test but with an additional crack across the center. For the third test, at the center of the block, there were no explosives but there was vibration wave impact of larger fragments. As such, the collision of vibration waves between the blast holes reduces the degree of breaking.

These experimental results indicated that, if delay time is much longer than the time needed to produce wave interaction, then the degree of disruption is the best. However, if it is too long, the degree of breaking will be decreased [10].

Yang and Rai [11] investigated the effect of row-to-row delay time on full-scale degree of breaking and particle size distribution at the Century Cements limestone quarry in Raipur, India. Two delay time samples were tested of 17 and 25 ms, corresponding to the "delay time/stage resistance" ratios of 8 and 12 ms/m respectively. Measurement of particle size and size distribution was performed using digital image analysis software. The results show that the 17 ms delay sample gives better smashing. This means that the difference in delay time affects the degree of rock crushing. However, these are two average delay time samples, which are not representative of the short and long time ranges.

Especially in recent years, thanks to the development of computer technology and control technique, research is spread across all aspects helping explosions to be almost completely controlled [12, 13]. All factors affecting explosive efficiency are taken into account. Modeling and simulation solutions using software tools can simulate the evolution and results of an explosion based on a continuously updated database. Many research studies can be carried out such as: solutions for data analysis and forecasting [10]; simulating the effect of the amount of explosives creating an explosion vibration [14]; simulating the propagation of blasting vibration waves [15], rock vibrations [16]; simulating the results of explosions [2, 8]. The simulation model results are an effective tool to test different adjustments and control solutions, thereby finding the most suitable explosion parameters.

As the main and basic effect, blasting vibration wave is the most interested research. The wave characteristics are digitized, divided into small groups and analyzed according to each stage and characteristic [13, 10]. These studies used different techniques and algorithms based on the computational speed of the computer [17–19]. Engineering and technology development makes it possible to digitize and differentiate wave characteristics with high precision. The information obtained is more complete and the applied analysis algorithms are also more complex.

Most studies aim to predict the level of blast vibration, the level of smashing and the level of cracking [20, 21]. Forecasting methods are based on recognition techniques using artificial neural networks along with various algorithms [22–24]. Some recent studies have chosen to apply artificial intelligence and machine learning techniques to improve forecasting accuracy [25, 26].

In developed countries, lots of synchronous equipment and software systems have been built based on these research results. Fig. 2 describes the process of performing a mine blast, in which the information from multiple inputs is systematically used. The BIMS (Blast Information Management System) software uses this information as database to analysis, design and build parameters for the next explosion.

A complete and detailed database plays an important role in this system, so it requires modern and highly accurate measuring and monitoring equipment, such as:

- flycam, camera with high resolution, high recording speed;
- system of monitoring and forecasting equipment for geology, climate and weather;
- the monitoring system of vibration level after an explosion. Furthermore, controllers, high-tech construction and explosion equipment are also needed to meet the software's calculation results.

For instance: blast hole drilling and setting equipment, explosive control equipment and detonators.

In delay blasting techniques, devices such as electronic delay blast controllers or electronic detonators make delay time extremely simple to control. Thanks to the ability of controlling blast to each mine hole, the delay time value can be flexibly controlled to meet all software calculation results. At the same time, these devices have a very high level of safety. Fig. 3 describes two explosion control solutions that are commonly used in countries with developed mining technology. Fig. 3 depicts the explosion control structure with the detonation device. Communication information is encrypted with high security to ensure there is no unintended explosions and silent mine phenomena are completely controlled.

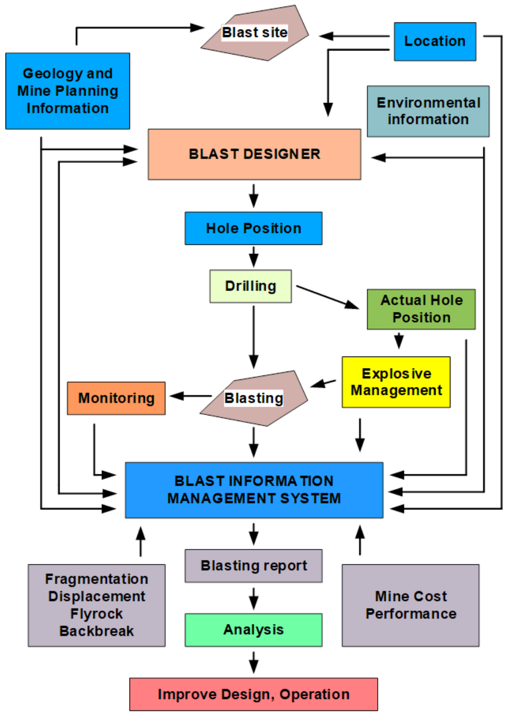


Fig. 2. System structure and process of designing and constructing a blasting with the support of BIMS (Blast Information Management System)

Systems using high-tech equipment and BIMS software have been achieved high effectiveness. But it is difficult for developing countries to apply because of their high price, including equipment procurement costs, operating costs and maintenance costs.

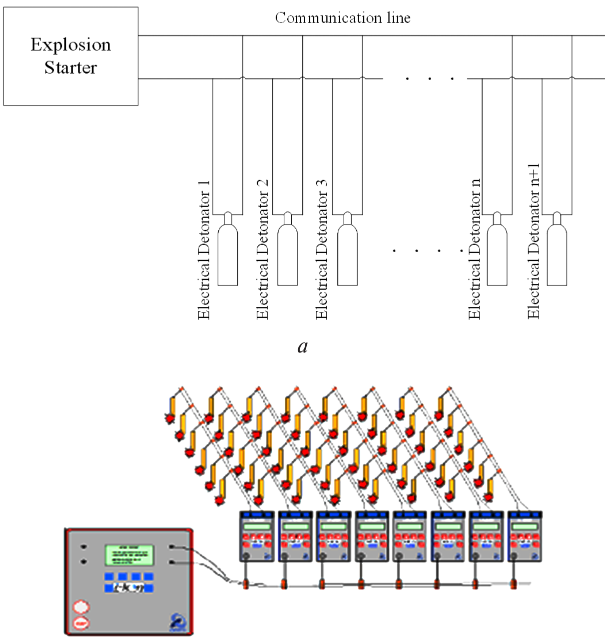
In recent years in Vietnam, popular technologies studied in blasting have been electronic detonators; using drones to take photos before and after explosions in some quarries; using particle size measurement software. However, their results have not been widely used in practice. Blasting at mines is carried out mainly based on the experience of engineers with limited information. In some mines, old-style blasting equipment and out of dated technology are still being used.

The research in this paper was conducted based on basic theories of blasting techniques, analysis software systems and modern explosive devices. From there, the authors proposed a simple solution suitable to economic and technological conditions in VietNam to improve the efficiency of blasting.

Theoretical basis. Blasting for mining is an issue of utilizing the most of explosive energy with each type of structure and physical properties of rock in each mining area. At the explosion point, the energy generated compression wave and vibration wave in two stages. In this study, they are called Blast Energy Waves (BEW).

The propagation velocity of BEW and the delay time value has a close relationship. Technically, it is easy to measure the propagation velocity. However, those measurement techniques have only been used in experiments and not in actual mine explosions. Besides, the vibration level of rock particles caused by BEW is the basis for evaluating the effectiveness of using explosives as well as the crushing efficiency of the explosion. So, it can be seen that a complete analysis of vibration wave data can provide important information for delay time selection.

If we assume that all explosion parameters remain unchanged, the delay time value now depends entirely on the rock and soil properties in the explosion area. Then, the research focuses on two main contents: to analyze vibration wave data to identify the current state of rock in the explosion area; to determine the appropriate delay time value to improve smashing efficiency.



a

b

Fig. 3. Blast control solutions for every drill hole:

a – the system using electronic detonators; b – the system using the solution of grouping boreholes with intermediate controllers

The optimality of the identification model depends on two basic factors: the accuracy of the data and the amount of collected data. Because the duration of a mine explosion is very short, data needs to be gathered from many explosions over time. This is the reason why the data is not synchronized. Therefore, boundary conditions are needed, as followed:

1. All parameters of the explosion are the same except for the delay time value.

2. The implementation process follows technical standards and explosive energy is fully utilized.

3. The value of delay time is within the allowable limits of designed value.

With those boundary conditions, the energy generated at the explosion points is the same and equal to the sum of the compression wave energy and the vibration wave energy. The vibration wave amplitude presents the effective use of explosive energy. Identification model uses vibration wave amplitude to determine the delay time value at which vibration level is minimal. This means that the model is both capable of determining a reasonable delay time and predicting the vibration level. The results of measuring the vibration during explosion will be important information to evaluate the effectiveness of using explosive energy and the reasonableness of the selected delay time value, from which the model can make necessary adjustments.

The identification model is built based on the information including: delay time value; average propagation speed of the vibration wave; maximum amplitude of the vibration wave. In particular, for each change in the delay time, there will be a pair of corresponding values of the model: wave propagation velocity and maximum amplitude. This pair of output values will then be used as reference information to calibrate the model's input values to minimize the vibration level.

Because the collected data cannot meet all the set boundary conditions, information including the distance from the explosion point to the point and the largest instantaneous explosive is added in this research to increase the accuracy of the model. On the other hand, the accuracy of the input data source determines the identification result and directly affects the prediction and control results. Therefore, data needed to be standardized through the process of identifying the sources of noise, providing solutions to eliminate interference or reduce it to a constant value. The structure of the control and forecasting system is described in Fig. 4.

With the above objectives, the research content focuses on:

1. Selecting areas to study and collect experimental data.

2. Developing solutions and performing data analysis.

3. Determining the relationship between the delay time value and the propagation velocity of BEW from the analysis results.

4. Building a model to determine the appropriate delay time for the study area.

Collecting and analyzing data. ***Data acquisition.*** The research area selected is Nui Beo coal mine, in Ha Long city, Quang Ninh province, Vietnam.

The device used to measure the level of vibration is Blastmate III from Instantel, Canada. Some technical specifications of the Blasmate as follows.

Components:

1. The device of reading and writing data.

- recording and deleting measurement data from the sensor along with necessary application information for the user (time, measurement location, management unit, information about the measurement object);
- recording interval for each measurement: 1–90 s;
- sampling rate: 1024, 2048, 4096 samples/s;
- memory capacity: 15 MB. Stores data for 1000 measurements at sampling rate of 2048 samples/s and recording time of 1 s. Expandable to 60 MB;
- vibration range that can be recorded: 0.2–30.0 mm/s;
- can connect to modem for remote control. Connect an external USB for easy data copying;
- printing results right at the scene in graph form.

Power source: 6–12VDC rechargeable battery.

2. Geophone.

- Measuring range 0.127–254 mm/s.

To ensure the analysis is accurate, the data collection process needs to follow certain principles such as:

- collected vibration wave data is fully and continuously recorded over time;
- the mine explosions are delay mine explosions carried out in the same area;
- direction of installation of measuring equipment relative to direction of detonation; Measurement methods and procedures are unchanged.

Data analysis. *Building analytical solutions.* In a certain area, in each stage, the vibration wave propagation speed is almost constant [2]. Therefore, in a delay mine explosion with many explosion points in different positions, detonated at different times, it will cause different vibration wave peaks at the measurement point over time. Thus, it is possible to interpolate the propagation speed of the vibration wave from analyzing the relationship of the delay time and the period between the two subsequent peaks and with the distance from the explosion points to measuring point.

In order to build a relationship between the delay time period and the propagation speed of BEW, the research aims to find a solution to analyze vibration wave data obtained from explosions during mining to determine relatively average propagation velocity of BEW from explosion point to measurement point.

Geology and topography are the most important factors influencing the wave propagation speed. However, because the selected and analyzed data are obtained from the same explo-

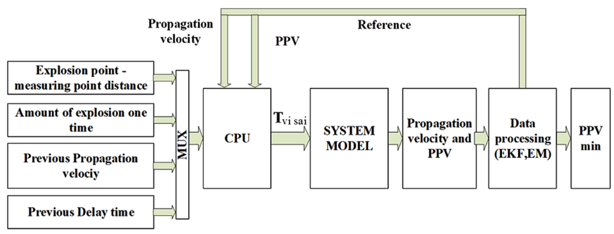


Fig. 4. Principle of delay time correction and prediction of vibration level for delay blasting

sion, these factors are the same. The propagation path of vibration waves from the explosion point to the measurement point which is considered the same. The direction of explosion is also an element that impacts the vibration wave, but it mainly affects the level of vibration. Thus, environment factors and explosion method can be ignored when determining the vibration wave propagation velocity of a delay mine explosion.

The solution is determined as follows.

Assumption: Two amounts of explosives placed at *A* and *B* are detonated sequentially with a delay time interval of ΔT milliseconds, $AB = 1$ m. The measuring device placed at *C* will receive two peaks of vibration waves corresponding to two detonations (Fig. 5). The possibilities are given in Table 2.

The data analysis algorithm determines the location of wave peaks and the time interval between peaks as depicted in Fig. 6.

Analysis results. Vibration wave data is described according to 3 *LVT* axes corresponding to the spatial coordinate system, in which the *L* axis is horizontal in the direction from the explosion point to the measurement point, the *V* and *T* axes are in the direction perpendicular to the *L* axis. *PPV* data describes the combined vibration of all three directions. Among the components of BEW, the longitudinal wave component with the greatest ability to break rock is described mainly in the horizontal direction. Therefore, in this paper, the authors analyzed two data sets: *L*-axis characteristics and *PPV* characteristics, respectively. This activity has two purposes of getting more reference results and determining data source suitable for the given requirements. Some analysis results are shown in Figs. 7, *a* and 8, *a*.

The vibration waves obtained at the measurement point are a combination of very complex interactions from the blast site, then they propagate in the heterogeneous rock environment. That causes a lot of noisy data.

Waves along the *L* axis have the fastest propagation speed. The analysis is only performed from the time the wave begins to be received until the time equivalent to the last explosion point according to delay time. So, the wave forms at this stage according to *L* axis data and *PPV* synthesis data is relatively similar. The results of analysis of about 497 cases in separate explosions proved that.

The analysis also shows that, in the middle of the explosion process, the interaction between energy waves is very complex. Data contains a lot of errors at that time. Therefore, only the first wave peaks should be selected for analysis due to the mutual influence of the waves is not much.

The analysis results are depicted in characteristic form in Fig. 9.

Identifying the relationship between BEW propagation velocity and delay time. With a large enough database, the system is identified by training an artificial neural network (ANN) model. The basic input data for training the ANN network is vibration wave propagation velocity and the delay time period. The output data is the vibration level.

After each new amount of data is added, the training process needs to be re-done.

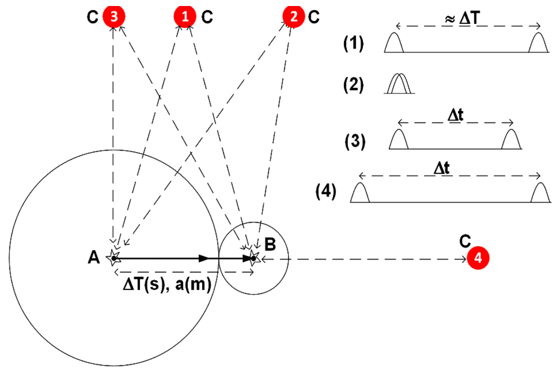


Fig. 5. Theoretical description of the method for calculating the velocity of propagation of vibration waves due to blasting

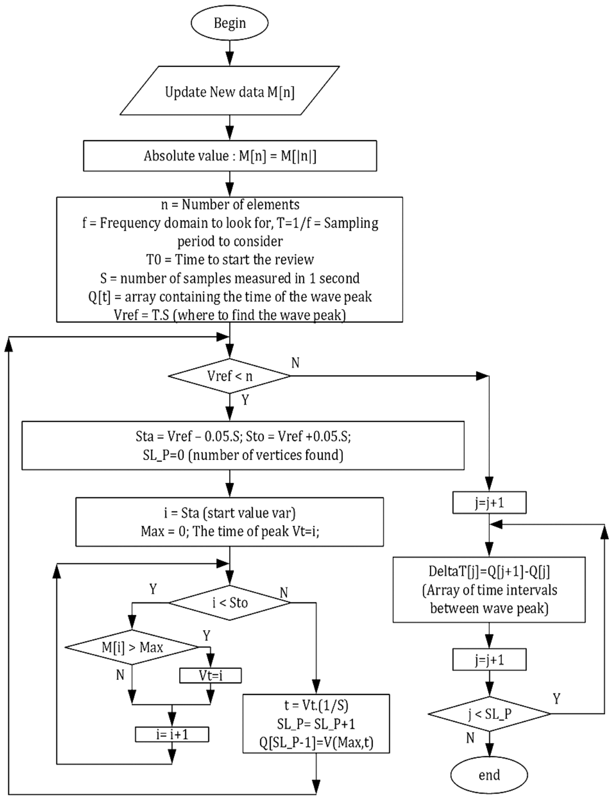


Fig. 6. Data analysis algorithm

In order to increase the accuracy of the model, some extra information is added, including:

- distance from explosion point to measurement point; delay times between consecutive mine holes or groups of mine holes;
- amount of explosive per explosion;
- propagation velocity of vibration waves.

Table 2

Cases that occur when calculating wave propagation speed

Measurement location *C*	Note	Calculation formula
No. 1	Distance $CA = CB$, the two wave peaks are independent: the time interval between the two wave peaks will be approximately the delay time ΔT as described in case (1)	Undefined
No. 3	1. If $CA > CB$, the two wave peaks overlap as described in case (2). 2. If $CA \neq CB$, the two wave peaks are independent, the time interval between the two wave peaks is Δt as described in cases (3) and (4)	$(CA - CB)/\Delta T$ $\lvert CA - CB\rvert/\lvert\Delta T - \Delta t\rvert$
No. 3	+) $CA \neq CB$, the two wave peaks are independent, the time interval between the two wave peaks is Δt as described in cases (3) and (4)	$\lvert CA - CB\rvert/\lvert\Delta T - \Delta t\rvert$
No. 4	+) $CA - CB = AB = a$ (m), the two wave peaks are independent, the time interval between the two wave peaks is Δt as described in cases (3) and (4)	$a/(\Delta T - \Delta t)$

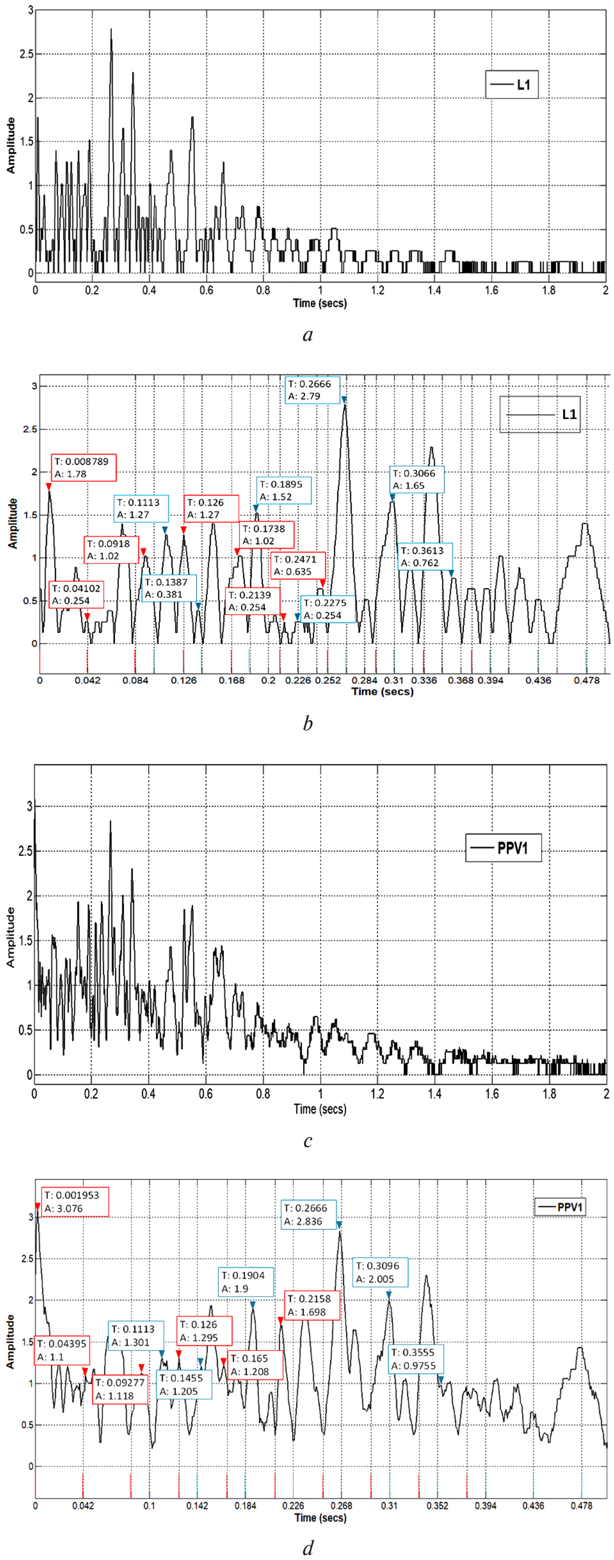


Fig. 7. Data analysis of a certain explosion number 01:

a – measurement results of Blastmate III in blast 01 (L axis); b – analysis of blast wave data 01 (L axis); c – measurement results of Blastmate III with explosion 01 (PPV); d – analysis of blast wave data 01 (PPV)

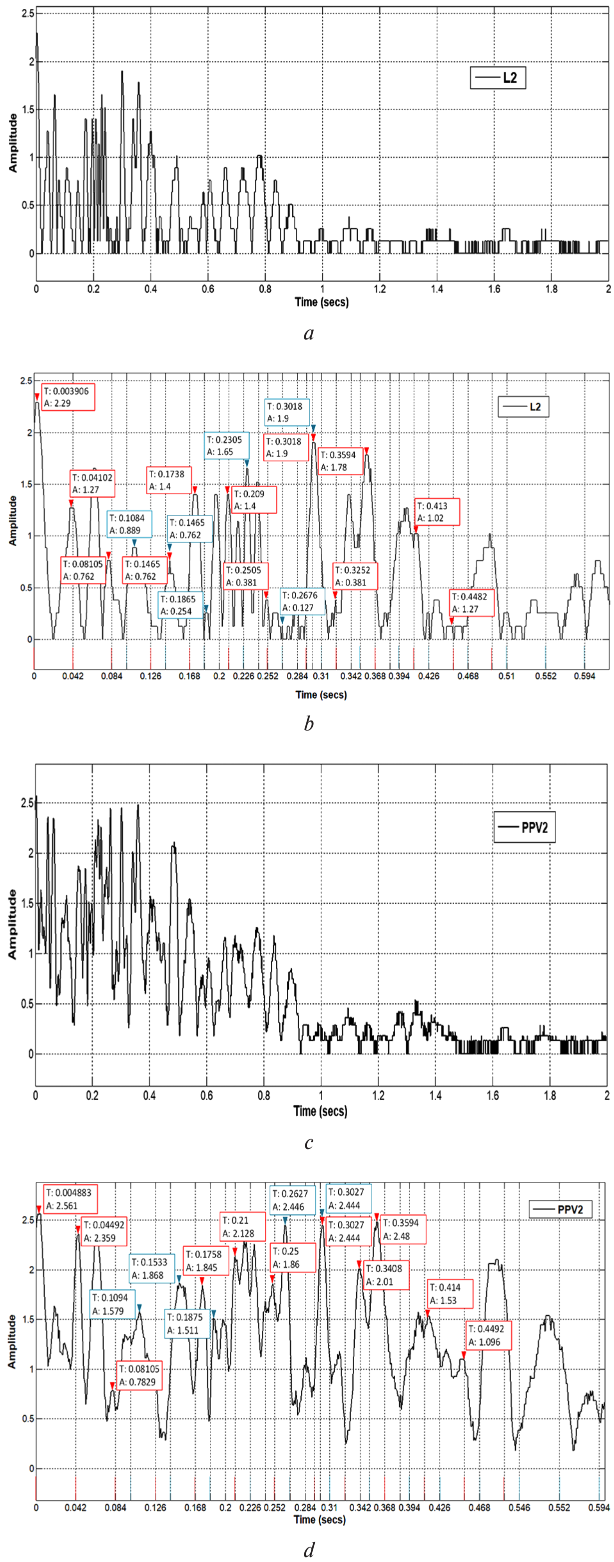


Fig. 8. Data analysis of a certain explosion number 02:

a – measurement results of Blastmate III with blast 02 (L axis); b – analysis of blast wave data 02 (L axis); c – measurement results of Blastmate III with explosion 02 (PPV); d – analysis of blast wave data 02 (PPV)

In particular, the propagation velocity value is calculated according to the data analysis method for each explosion, the remaining values are recorded in reality in the study area.

The general structure of the ANN model is described in Fig. 10. The training algorithm chosen is the backpropagation algorithm. Authors uses 75 % analyzed data set to build an identification model, the remaining 25 % will be used as a reference for evaluating the established model. The software used for training is Matlab2013.

The process of testing and analyzing results with different neural network structures shows that the network structure with two hidden layers with the training function "rainscg" gives the best results.

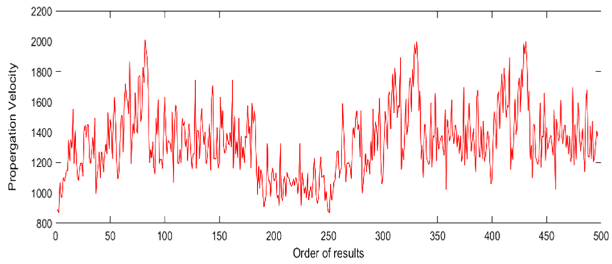


Fig. 9. Summary graph of analysis results

The optimal neural network structure found includes two hidden layers: the first and the second layer with 69 and 60 cells, respectively. Training process with 170000 epochs. The algorithm chosen is the "backpropagation algorithm" with the method for adjusting and updating the weights according to the scaled conjunction gradient principle, the training function is "trainscg". The transfer function of the hidden layers is chosen to be "tansig", the transfer function of the output layer is "purelin". The training result have built a neural network structure that simulates the research object – Custom Neural Network 1 (Fig. 11, *a*).

To test the quality of the identification model, 25 % of the previously left data corresponding to 100 datasets are used. These data are supplied to the Input Data port for the Custom Neural Network model, Fig. 12.

The two graphs depicting the results are quite similar (Fig.11, *b*). The deviation of the model's forecast results compared to the actual results is commonly below 2 %, about 13 % of forecast results having a deviation of 2–5 %. There was 1 result with a deviation of over 10 %.

Testing the model. According to the control and prediction principles (Fig. 12) along with the set boundary conditions, the identification model is the tool to determine the delay time for purpose of minimizing the vibration level. Tests were done by using obtained model for some cases, as follows.

Case 1: Simultaneously change the value of the delay interval time in the range of 8–22 ms. The amount of explosive is changed while the other parameters remain unchanged.

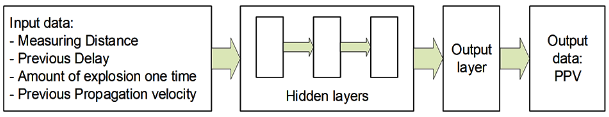
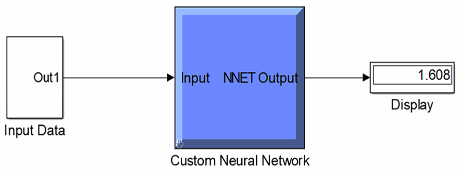
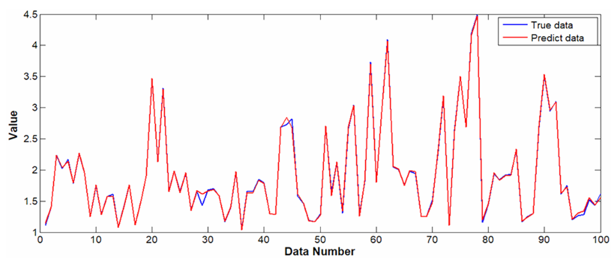


Fig. 10. General structure diagram of ANN model for system identification



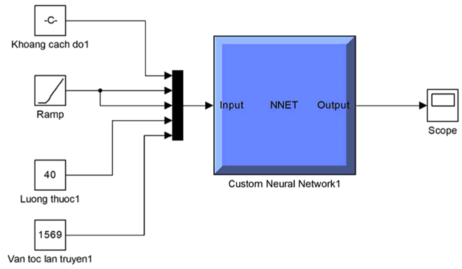
a



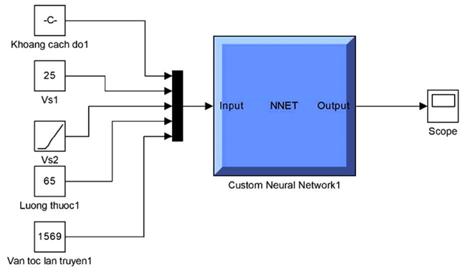
b

Fig. 11. Model testing results:

a – results of the built neural network; b – comparison between the value taken from the proposed model and the actual value



a



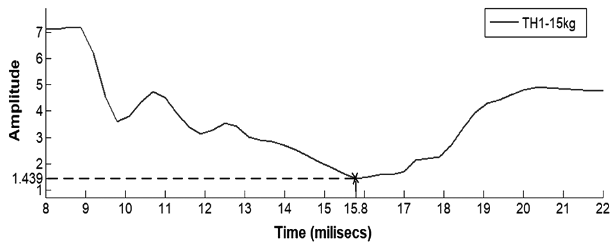
b

Fig. 12. Structure diagram depicting test cases:

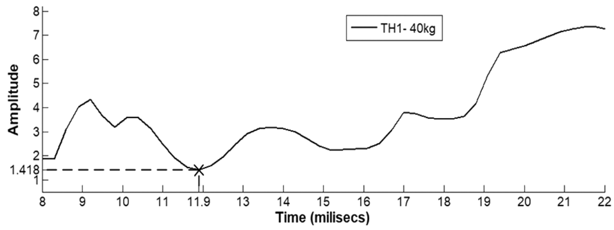
a – first case: both Vs1 and Vs2 change; b – second case: Vs1 = = const and Vs2 changes

The simulation structure diagrams performed on Matlab 2013 are shown in Figs. 12, *a, b* corresponding to case 1, case 2. The test results are shown in Figs. 13 and 14 respectively.

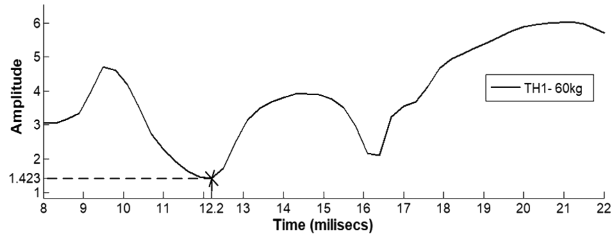
Case 2: All delay time values are within a specified range, one of which is constant, the others are varied. The deviation between the two values cannot be larger than the constant



a



b



c

Fig. 13. Test results for the first case:

a – the best delay time value is 15.8 ms, the predicted vibration level is 1,439 mm/s; b – the best delay time value is 11.9 ms, the predicted vibration level is 1,418 mm/s; c – the best delay time value is 12.2 ms, the predicted vibration level is 1,423 mm/s value to ensure that the delay diagram is not changed. Two tests were conducted with the constant value equal to 15 ms, variable values are from 8–23 ms and constant value is 25 ms, variable values are 15–35 ms. The amount of explosive is varied while the other parameters remain unchanged.

The results in Figs. 13 and 14 show that, when the maximum amount of instantaneous explosive changes, the delay time value also changes because the training data set is not uniform according to the set conditions. However, the test results in each case determine the appropriate delay value and predict the corresponding vibration level. The experimental results have met the model building goals.

Algorithm to determine delay time and predict vibration level. Based on the obtained model, a software can be built to determine the appropriate delay time and predict the vibration level for the next explosion. The delay time value is calibrated so that the expected vibration level is as small as possible. The initial time value is set to the value used in the last explosion. The software algorithm is described in Fig. 15.

Conclusion. Although the database is not guaranteed due to many influencing factors, adding more information has helped the training results identify an ANN network. Test results show that the identification model is relatively accurate. The experiments have demonstrated the method of building artificial neural networks to identify systems is completely appropriate. The model is a tool for delay timing correction.

The data used in this study is small and just for one area, the data variation is not much so it is not possible to describe all cases. The results are only valid within the used data set.

The result of training the neural network is a system transfer function with defined input and output data. The boundary conditions are as follows:

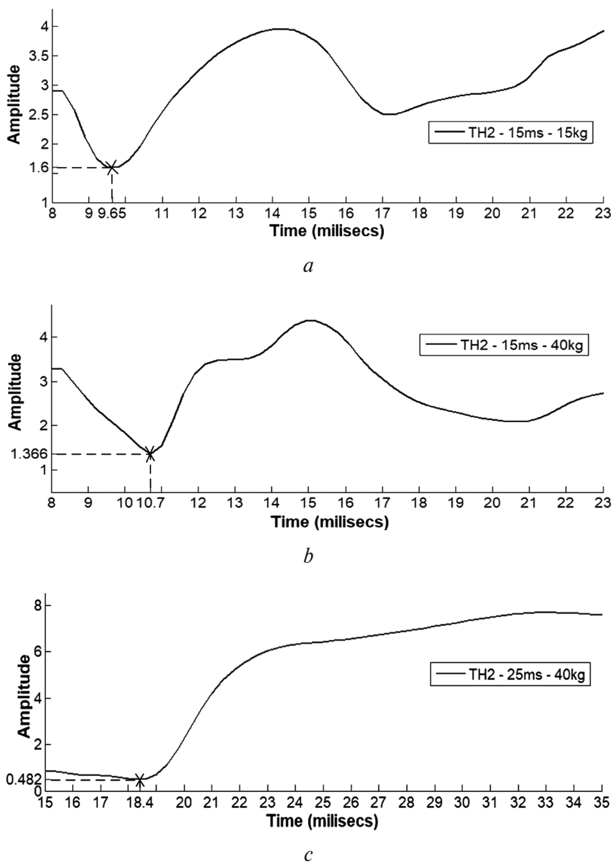


Fig. 14. Experimental results for the second case:

a – the best pair of delay time values is 15 and 9.65 ms, the predicted vibration level is 1.6 mm/s; b – the best pair of delay time values is 15 and 10.7 ms, the predicted vibration level is 1,366 mm/s; c – the best pair of delay time values is 25 and 18.4 ms, the predicted vibration level is 0.482 mm/s

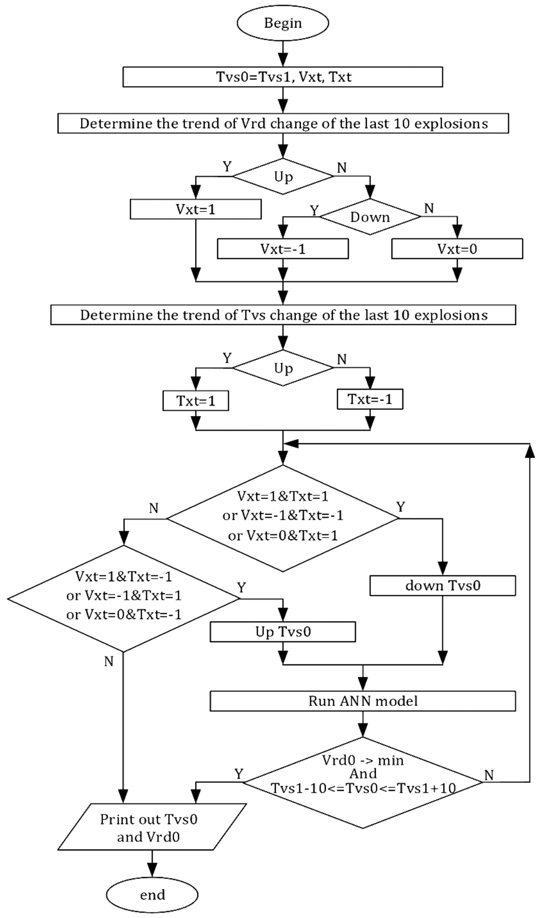


Fig. 15. Algorithm to determine delay timing and predict vibration level for the next explosion:

Vrd is peak vibration velocity; Tvs is delay time; Vxt is variation trend of wave propagation velocity; Txt is variation trend of set delay time values; Index 0 is for the next explosion; Index 1 of the explosion just performed

1. The design parameters of the explosions are equivalent except for the delay time.
2. The drilling and construction process ensures correct technique and design.
3. The distance, location, and direction of the sensor station from the explosion center are selected to be the same or equivalent in all explosions.
4. Explosions are carried out under basically the same weather and environmental conditions.

Then, the control structure is built with data of two inputs: wave propagation velocity and expected delay time, while the output is the predicted vibration level. However, in reality it is very difficult to meet all standards and conditions, so other data can be added to increase the accuracy of the model and better match reality.

Training a neural network and using it to build software that proposes delay times and predicts the level of vibration for the next explosion can be understood as a solution for building artificial intelligence algorithms. Perfecting an AI algorithm requires a lot of time for testing, analyzing results and adjusting. With the specificity of geology, each area will give a different model.

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Рішення з аналізу даних задля підвищення ефективності вибухових робіт у гірничодобувній промисловості

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Мета. Побудова ідентифікаційної моделі визначення відповідних значень параметрів підривних робіт із прийнятною вартістю. Оптимізація проєктування підривних робіт на кожній робочій ділянці з розрахунком часу затримки на базі моделі, що використовується.

Методика. Підривні роботи при видобутку корисних копалин – це питання використання максимальної енергії вибуху для досягнення найбільшої руйнівної здатності та найменшого рівня вібрації. У сучасних технологіях підривних робіт загальна кількість вибухової речовини ділиться на частини, що детонують через різні проміжки часу. Таке рішення створює інтерференцію між хвилями напружень, що призводить до зменшення міцності гірських порід і підвищення ефективності підривних робіт. Незважаючи на те, що час затримки відіграє важливу роль у цьому методі, досі його значення розраховують емпірично на місці вибуху через нерегулярні характеристики гірських порід. Також були визначені технічні проєктні параметри вибуху, включаючи час затримки, за допомогою програмного забезпечення інтелектуального аналізу та імітаційних моделей. Однак їх застосування обмежене через високу вартість і важкі умови реалізації. Методика, запропонована в роботі, усуває цей недолік і її ефективність доведена у процесі аналізу експериментальних даних на гірському масиві Нуй Бео у В'єтнамі.

Результати. Розроблена модель ідентифікації на основі даних, що включають у себе: значення часу затримки вибуху; середню швидкість поширення вібраційної хвилі; максимальну амплітуду вібраційної хвилі.

Наукова новизна. Використане базове програмне забезпечення для аналізу даних і модель штучної нейронної мережі. Створено новий алгоритм аналізу даних для визначення оптимального значення часу затримки вибуху.

Практична значимість. Сформоване просте та економічно обґрунтоване рішення з підвищення ефективності підривних робіт при видобутку корисних копалин.

Ключові слова: *вибухові роботи, ідентифікаційна модель, аналіз даних*

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