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NON-DESTRUCTIVE TESTING OF ROCK BOLT FASTENING AS AN ELEMENT OF MONITORING THE STATE OF MINE WORKINGS

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ABSTRACT

Purpose. To substantiate the informative parameter, to develop the method and equipment for non-destructive testing (NDT) of rock bolt fastening, as an element of geomechanical monitoring of the mine workings state.

Methods. Analytical and bench experimental testing of shock-wave processes in the "rock bolt – bonding layer – rock massif" system.

Findings. It has been established, that the non-destructive shock-wave method is the most satisfying for monitoring the geomechanical state of the "rock bolt – bonding layer – rock massif" system. This method is based on the registration and analysis of rock bolt oscillations, caused by non-normalized hit to the rock bolt end. It has been confirmed, that the most informative parameter is the relaxation time, that is the time over which the amplitude of oscillations decreases by "*e*" times. It has been shown, that clamping of the resin-grouted rock bolt in massif and its tensioning affects the relaxation time of damped oscillations. Furthermore, the relaxation time is inversely proportional to the degree of the rock bolt clamping, and is linked linearly with an increase in the rock bolt tensioning. The spectral composition of wedge shaped rock bolts self-oscillations, which are caused by impact excitation, depends both on the nature of clamping and on the rock bolt length, and makes it possible to identify the rock bolts by their length.

Originality. The existence of a special type of damped longitudinal oscillations of the rock bolt in viscoelastic medium of the bonding layer has been established. The relaxation time of the specified type of oscillations was chosen as an informative parameter. An analytical link has been established between the informative parameter of shock-wave method of monitoring and the main indicators of rock bolt fastening quality: the degree of adhesion with massif and tension value.

Practical implications. The method has been improved and equipment has been developed for non-destructive testing of rock bolt fastening, which makes it possible to control in-situ the rock bolt fastening quality, including the geomechanical state monitoring of mine workings.

Keywords: *mine working, monitoring of state, rock bolt, non-destructive testing, method, equipment and methods of control*

1. INTRODUCTION

The mining industry is among the "leaders" in terms of the number of accidents, hard labor, capital investments volume and production infrastructure complexity. If to exclude the human factor, then 70 – 80% of accidents in mines are caused by various geomechanical factors: rock pressure and its manifestations, stress-strain state of the rock massif, support and security structures state, etc. The rock massif geomechanics affects significantly the production costs volumes (Wang, Hagan, & Cao, 2016). It is possible to reduce these costs and increase the production safety by optimizing the fastening technology of the underground workings when simultaneous introducing a system control (monitoring) of their geomechanical state (He, Van Velsor, Lee, & Rose, 2006; Zou & Cui, 2011; Moridi, Sharifzadeh, Kawamura, & Jang, 2018; Tamrakar, Asaue, Shiotani, Chang, & Fujiwara, 2018).

At present, the most progressive technology of rock bolt fastening is used in production of most iron ore and non-metallic mines, as well as in almost half of mine workings in the coal mines of Ukraine. This is widely used in the "New Austrian" and other methods of civil construction (metro, transport tunnels, underground storages) (Li, 2017).

However, the rock bolts have two significant drawbacks. Firstly, there are high requirements for compliance with the construction technology, especially with such parameters as the rate of constructing, the rock bolt length and angle of inclination, diameter of the borehole, the characteristic of the binder, its quantity and filling uniformity, and tightness of the borehole. The rock bolt adhesion with the rock massif, its load-bearing capacity and, as a result, the mine workings stability depends on this. Secondly, the inability to visually monitor the rock bolts state. In practice, the method of determining the force of mechanical pulling of the rock bolt is periodically used (Zhao & Yang, 2011; Bastami, Shahriar, & Ghadimi, 2017; Liu, Wang, Huang, & Jiang, 2017; Thenevin et al., 2017). This method is effective only for selective monitoring because it belongs to destructive class of control. The monitoring recommended by the industry standard of SOU Ukraine 10.1.05411357.010:2014, for example, includes the use of contour and depth indicators with a very coarse grid – one controlled rock bolt in the interval from 20 to 100 m of mine working. The existing non-destructive methods for monitoring the rock bolts developed in the USA, Russia and other countries (Ivanovic & Neilson, 2013; Forbes, Vlachopoulos, Hyett, & Diederichs, 2017), solve the problem only partially, for the following reasons. Firstly, they mostly use the spectral composition of rock bolt oscillations as an informative parameter, which complicates significantly the equipment and information processing method (Voznesenskiy, Koryakin, & Voznesenskiy, 2016). Therefore, they are mainly used for research work or limited control in particularly problem areas. Secondly, they have a low protection level against acoustic disturbances, which constantly accompany mining production (Shi et al., 2018). Thirdly, they do not provide for the accumulation and automatic processing of control data, which is extremely important for improving ergonomic indicators and the assessment quality with a non-normalized force of oscillations excitation.

Therefore, the purpose of the work was stated – to improve the method and develop the means of monitoring the geomechanical state of the "rock bolt – rock massif" system for operational assessment in the mode of monitoring the quality control of rock bolt fastening in the rock massif and its loading under conditions of existing production in the mine workings.

2. METHODS

The theoretical and experimental research methods, as well as results analysis and synthesis are used in the work. When developing the methodology, the materials of papers (Blanco-Martín, Tijani, Hadj-Hassen, & Noiret, 2013; Kang, Yang, & Meng, 2015; Li, Kristjansson, & Høien, 2016) were used.

The experiments were performed on two special test benches. The schemes of these benches are presented in Figures 1 and 2. The oscillatory processes were studied on a steel rock bolt of 22 mm in diameter, 1.2, 2.4 and 2.7 m in length. The oscillations, caused by hammer impact on the rock bolt end, were registered by the special sensor, mounted on the side surface of rock bolt free part, and then they were transmitted to a computer, where the special SpectraLab software was used to process data.

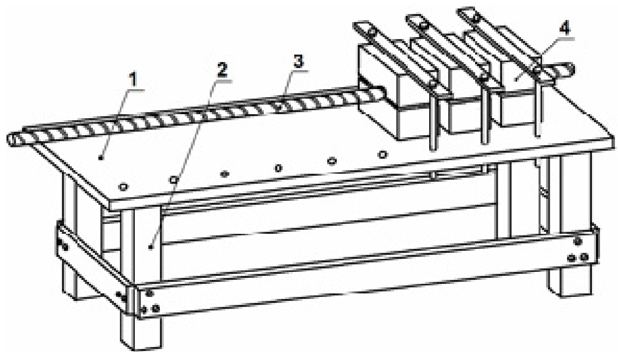

Figure 1. The first test bench structure: 1 – platform; 2 – support bearing; 3 – rock bolt; 4 – clamping element

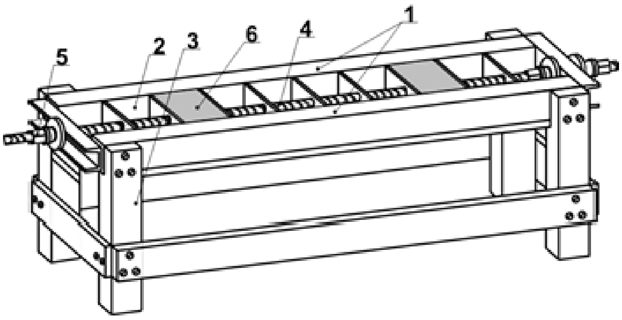

Figure 2. The second test bench structure: 1 – tray; 2 – tray section; 3 – support bearing; 4 – rock bolt; 5 – nut; 6 – hardening filler

The characteristics change of the rock bolt with different conditions of its clamping were modeled on the first test bench. The clamping conditions (from pointwise to close-set) were provided by special removable components. The second test bench was used to study the oscillation processes with different tension of the rock bolt. The forcing was created with a torque wrench and fixed with binder (concrete or polymer). The purpose of the experiment was to establish the dependence of the rock bolt self-oscillations parameters on the quality of its fastening, and to determine the informative parameter of the control method.

The theoretical studies were carried out using the known oscillations theory principles and mathematical statistics.

A simplified mathematical model of dynamic interaction in the "rock massif – rock bolt" system is a rock massif with delamination of some arbitrary thickness, in which a borehole was drilled. The rock bolt is set into the borehole, which contacts with the rock through a bonding layer (polymer, concrete, etc.). A certain force hit is applied to the rock bolt end. The body of rock massif with delamination and the rock bolt is equal to m and is proportional to the rock bolt length l. The bonding layer has a rigidity k and viscosity η. The force of impact excitation of the rock bolt along the conditional X axis of the rock bolt, is equal to F_i.

Three variants of boundary conditions are considered:

a) rock bolt is clamped on one end without bonding layer;

b) rock bolt is clamped on both ends without bonding layer (wedge type rock bolt);

c) the rock bolt is fully clamped along its length in viscoelastic medium (resin-grouted or cemented rock bolt).

The purpose of these research is to establish an analytical link between the control method informative parameter and the quality characteristics of the rock bolt fastening, as well as to improve the method results reliability.

3. RESULTS AND DISCUSSION

The method of rock bolt fastening quality and its load-bearing capacity control is based on the patterns of rock bolt interaction with the rock massif, as well as the oscillatory processes in the "rock massif – bonding layer – rock bolt" system, caused by external dynamic impact. The source of this impact is a hit to the rock bolt end.

When performing theoretical studies, it was taken into account that in a real situation there are several forms of rock bolt longitudinal oscillations with various physical nature:

– based on the rock bolt material and geometry, considering its boundary conditions of fastening on different ends without contact with medium (variants "a" and "b");

– determined by the rock bolt movement as an absolutely rigid rod in a viscoelastic medium (variant "c").

Frequencies spectral composition for variants "a" and "b" is determined by:

$$\omega_k = \frac{(2n+1)\pi V_p}{2l}; \quad \omega = \frac{n\pi V_p}{l}, \tag{1}$$

where:

V_p – longitudinal wave velocity in the rock bolt;

$n = 1, 2\ldots\infty$.

Steel bolt main oscillations frequencies, depending on its length, are given in Table 1.

Table 1. The main frequencies of oscillations for rock bolts

Rock bolt length, m	Frequency, Hz	
	variant "a"	variant "b"
1.2	6618	13236
1.8	4413	8826
2.4	3309	6618
2.7	2942	5584
4.0	1986	3972

In case of a resin-grouted rock bolt or cemented rock bolt, the rod oscillations in a viscoelastic medium, the rigidity of which is much less than the rock bolt material itself (variant "c"), occur much more complex. In the static position, the rock bolt is under the tension force P_0. When being hit, the rock bolt acquires an initial velocity, the vector of which is directed along the X axis. In the opposite direction, a viscous resistance force will act, the value of which is proportional to the current velocity of the moving mass and the length of the rock bolt, as well as an elastic force with the value proportional to the current displacement x. Due to these forces, the rock bolt velocity will decrease, and the direction of mass acceleration will be negative relative to the X axis orientation. In general case, this process can be described by the expression:

$$x = \frac{P_0}{k} + A_0 e^{-\left(\frac{\eta l}{2m} + i\frac{\sqrt{4mk-\eta^2 l^2}}{2m}\right)t}, \tag{2}$$

where:

A_0 – initial amplitude of rock bolt oscillations.

The physical significance of the first summand is the static elastic deformation of the rock bolt tension, which is determined by the pretension value. The second summand is the comprehensive recording of spring pendulum damped oscillatory process in a viscous medium. In this case, the rock bolt performs longitudinal oscillatory movements along the borehole axis as a single unit. Other forms of oscillations (longitudinal, transverse, and torsional) are caused by alternating elastic deformations of the rock bolt material itself and depends less on contact conditions with the surface of external medium.

The second exponent expression describes the frequency, which in a complex way depends on the two main indicators that determine the rock bolt fastening quality – rigidity indicator k and viscosity coefficient η. These parameters are reduced with fastening quality deterioration.

It was established experimentally that:

– the rock bolt longitudinal self-oscillations frequency, due to its contact with a viscoelastic medium, is 2 – 6 times lower than the main oscillations frequency in the rock bolt material and depends on the elastic properties of the material and conditions of the rock bolt clamping on the ends;

– the deterioration of the quality of rock bolt fastening in the viscoelastic medium leads to a decrease in the frequency of the spectral density maximum of oscillations and an increase in the initial amplitude of oscillations.

The spectrum of loosely fastened rock bolt is shown in Figure 3, and the normally fastened rock bolt is in Figure 4. These spectra determine the operating frequency range, which depends only on the contact conditions of the rock bolt with the bonding layer viscoelastic medium. For the rock bolts from 1.2 to 2.7 m in length it ranges from 0.5 to 1.5 kHz. There is a tendency of frequency increase of spectral density maximum with a decrease in the rock bolt length, but a small number of available rock bolts with different lengths (1.2, 2.4 and 2.7 m) prevents from establishing the reliable analytical link between these parameters.

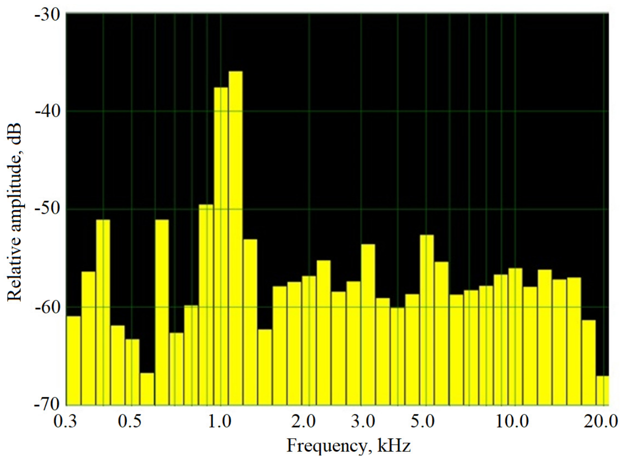

Figure 3. The oscillations spectrum of a loosely fastened rock bolt of 2.4 m in length

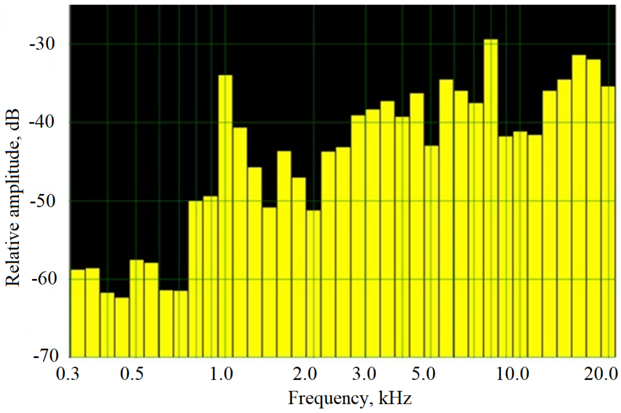

Figure 4. The oscillations spectrum of a normally fastened rock bolt of 2.4 m in length

The low frequency components of oscillations are associated with the inertia of the "rock bolt – bonding layer – rock massif" system and are manifested in the total spectrum of oscillations with a certain delay relative to higher frequencies, which is explained by a rather high sound velocity in the rock bolt material.

Owing to this inertia, the oscillations in the low frequency area of the spectrum attenuate more slowly. Therefore, for efficient extraction of low frequency components, it is advisable to analyze the oscillatory process with a small delay relative to its beginning. The degree of attenuation is determined by the value of attenuation coefficient β or its reciprocal value τ (relaxation time):

$$\tau = \frac{1}{\beta} = \frac{2m}{\eta l} = \frac{C}{\eta}, \quad (3)$$

where:

C – constant value, determined by the rock bolt design and geometrical parameters.

The physical significance of the relaxation time is the time interval during which the amplitude value of damped free oscillations decreases by "e" times. The main advantage of this parameter is that it does not depend on the initial amplitude of oscillations, i.e. the force of hit.

On the first test bench, it was established experimentally that the relaxation time of rock bolt free oscillations is inversely proportional to the parameter p, which characterizes the quality of the rock bolt fastening in the rock massif:

$$\tau = \frac{B}{p}, \quad (4)$$

where:

B – experimental coefficient.

On the second test bench, it was also experimentally established that the relaxation time of free oscillations depends linearly on pretension force F_n:

$$\tau = \tau_0 - kF_n, \quad (5)$$

where:

τ_0 – the relaxation time of free oscillations without rock bolt tensioning.

The summarizing result – the relaxation time takes into account the rock bolt clamping and its tensioning:

$$\tau = \frac{B}{p} + b, \quad (6)$$

where:

b – the component, determined by the rock bolt tensioning, which decreases with its growth.

Thus, the relaxation time of free oscillations of the rock bolt fastened in the rock massif is determined by two components. The first component is inversely proportional to the rock bolt force of resistance, and the second one decreases linearly with increase in the rock bolt tensioning. Note, that the first component can be neglected for the wedge type rock bolt, since it is clamped in two points. Therefore, the informative parameter "τ" will provide information only about the rock bolt tensioning and decrease linearly with an increase in loading.

The established patterns of the change in the spectral composition of the rock bolt free oscillations and the parameters of their attenuation depending on clamping form the basis for the method of quality control for the rock bolt rod fastening in the borehole. The method is patented in Ukraine (Patent 122418, IPC E21D, 20/00). The method involves the sequential performance of the following operations: to hit the rock bolt end, exciting free oscillations in it, preliminary analysis of the spectral composition of oscillations, identification of a frequency band with a maximum spectral density, performing an amplitude signal selection, delaying the signal analysis until the end of the transition process, determination of the relaxation time as informative parameter (Skipochka, Serhiienko, & Krasovskyi, 2017; Skipochka, Serhiienko, & Krasovskyi 2018).

To implement the method for quality control of the rock bolt fastening, new microprocessor equipment, based on combined experience, has been created – Complex-Vibro-Acoustic Control (CVAC). It allows to perform the initial statistical processing of information with pre-programmed parameters. The information is displayed on the LED display.

CVAC device and its elements can be seen in Figure 5.

Specifications of the CVAC equipment:

– the range of parameter determination is 0 – 999 ms;
– resolution – 0.1 ms;
– frequency band pass – 200 – 1500 Hz;
– minimal input signal level – 0.2 V;
– power voltage – 6.0 – 9.0 V;
– block dimensions – 90×125×155 mm;
– unit weight with power package – 1.7 kg.

The specialized software is used in the CVAC equipment, which has individual features of preparation for work. Before to start the work, it is necessary to reprogram the device based on specific control tasks. The informative parameter "τ" is determined for 0.3 s and stored in the device memory. When obtaining the first results, the accumulated data goes through primary statistical processing program, which determines the average value, the standard deviation, the average absolute error of the maximum permissible absolute and relative errors.

The program compares the calculated value of the limiting relative error δP_1 with the predetermined value of the permissible relative error δP_2. If $\delta P_1 < \delta P_2$, the cycle ends, display shows line "end of the cycle", the arithmetic average parameter value and its limiting error.

(a)

(b) (c) (d)

Figure 5. CVAC equipment: (a) main device (electronic package); (b) clip-on sensor for the rock bolt; (c) contact sensor for arbitrary designs; (d) hammer

Otherwise, there is a further accumulation of the dataset with recalculation of parameters after each new value. The anomalous values are excluded. The input data processing is terminated automatically when the specified accuracy is reached. The values that can be reprogrammed are: the volume of the original dataset N, confidence coefficient α and permissible relative error. With an increase in N and in α and with a decrease in δP_2, the method informative value is improved. At the same time, the time increases for performing one cycle of the equipment operation. Therefore, when programming, it is necessary to determine the priority – high reliability of data or the rate of control.

The device can be reprogrammed using a computer with installed special software. The recommended parameters values for typical situations are shown in Table 2.

Table 2. Programmable parameters for statistical data processing

Parameter for statistical processing	Control task		
	calibrating	sample estimate	mass assessment
N	8 – 10	5 – 7	5
α	0.95	0.90	0.80 – 0.90
δP_2	0.05	0.10	0.10 – 0.15

The control technology includes: sensor installation on the rock bolt tail joint, hammering the rock bolt end with a series of hits, and recording the final values of the informative parameter. The control process is shown in Figure 6.

Figure 6. Example of shock-wave method for the quality control of the rock bolt fastening

Since there are no universal criteria for shock-wave method for quality control of the rock bolt fastening, it is necessary to calibrate the device for a specific type of the rock bolts and the technology of their fastening. The task of calibration is to establish the dependence between the non-destructive and subsequent destructive testing. The object of calibration is a set of rock bolts fastened in the rock massif using the same technology of fastening. The rock bolt load-bearing capacity is used as an indicator of the quality of the rock bolt fastening, which is determined by destructive method of control in mine conditions. According to the value of indicator, the quality of fastening can be divided into three categories: “above normal”, “normal” (within the ±20% range of acceptable deviations) and “below designed”. The total number of rock bolts for calibration in each group must be at least three categories of rock bolts. The calibration efficiency is achieved by simultaneous increasing the reliability of non-destructive and destructive testing results. Due to the impossibility of repeated destructive testing, its reliability can be improved only by increasing the number of rock bolts to be tested.

In non-destructive testing of the area fastened with the rock bolts, the previously obtained calibration dependence is used. The reliability of testing can be improved by increasing the number of informative parameter determinations. The recommended ratios between the sizes of controlled rock bolts batch and the corresponding sizes of samples are given in Table 3.

Table 3. Recommended ratios between the sizes of controlled rock bolts batch and corresponding sizes of samples

Batch size, pcs.	Recommended sizes of samples for testing, pcs.		
	weak	normal	enhanced
25 – 50	5	8	13
51 – 90	5	13	20
91 – 150	8	20	32
151 – 280	13	32	50
281 – 500	20	50	80

The primary laboratory processing of data includes:

– the sequential selection of each rock bolt state, depending on the control tasks, into one of three or two (the norm or defect) gradations using the calibration dependence;

– determining the number d of defective rock bolts in the current sample.

The agreed with a consumer, an acceptable AQL quality level serves as the criterion for assigning the bolted area based on a controlled sample. From the standard range of AQL values, taking into account the actual fastening in mines conditions, the range from 1 to 10% has been selected. If $d \leq A_c$ is satisfied for the selected AQL value (where A_c – permissible amount of defects), then the area meets the requirements for fastening and should not be controlled. In case, when $d \geq R_e$ (where R_e – prohibitive amount of defects) the area as a whole is considered defective.

In addition to quality control of the rock bolt fastening, the CVAC equipment allows to observe the dynamics of delamination development in the border zone of mine working, both in its fastened areas and in the areas without fastening. One of the control types is the identification of delamination areas of shotcrete coating at the combined rock bolt fastening “rock-bolt – shotcrete”. The physical basis of such control is an increase in the quality of self-oscillations of the rock or concrete layer that have lost close mechanical contact with the rock massif. A consequence of this process is an increase in the relaxation time value.

For this type of control, a contact sensor with a conical concentrator is used. The control point position is determined. The contact vibration sensor is pressed perpendicular to the surface of mine working at a distance of about 1 m from the controlled point. After switching on the equipment, a preliminary hit is applied at a controlled point to assess its performance. In the case when a result is different from zero, the equipment is considered ready to work. At a controlled point, a consistent series of hits is applied. The quantity of determinations of informative parameter at one point corresponds to the conditions of mass control.

In general case, there are three gradations of the rock massif state: “monolith”, “explicit delamination” and “intermediate state”. The criteria values for the assigning the controlled points to a certain category are determined by means of calibrating at the experimental areas, where the rock massif structure is predetermined by control drilling. The zones of delamination are distinguished according to control results of certain points. The dynamics of their development over time can be studied by performing the consistent periodic monitoring.

4. CONCLUSIONS

The stability of mine workings and the labor safety of miners significantly depend on the quality of the rock bolt fastening. The variability of the mining and geological conditions of mine workings construction and significant impact of mining operations on their state require a constant control of the “rock massif – mine workings – support” system in the mode of monitoring. This can be achieved by means of NDT methods.

It has been established by means of theoretical and experimental studies, that the problem can be solved by shock-wave control method. The modification of this method, based on excitation, registration and analysis of the rock bolt self-oscillations, has been developed.

The informative parameters of the method have been determined, and the analytical expressions have been obtained that connect them with the quality of fastening and load-bearing capacity of the rock bolt. A method of non-destructive rock bolt control has been developed and patented. In relation to other tasks, the possibilities have been shown of the rock massif geomechanical monitoring development.

According to the research results, a methodology and equipment for quality control of the rock bolt fastening have been developed, which is expedient to use in coal and other mines, as well as in underground civilian objects for monitoring the state of the “rock bolt – rock massif” system and as part of the system geomechanical monitoring of underground and embedded structures.

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НЕРУЙНІВНИЙ КОНТРОЛЬ АНКЕРНОГО КРІПЛЕННЯ ЯК ЕЛЕМЕНТ МОНІТОРИНГУ СТАНУ ГІРНИЧИХ ВИРОБОК

С. Скіпочка, О. Круковський, В. Сергієнко, І. Красовський

Мета. Обґрунтування інформативного параметра, розробка способу та апаратури неруйнівного контролю анкерного кріплення як елементів геомеханічного моніторингу стану гірничих виробок.

Методика. Аналітичні та стендові експериментальні дослідження ударно-хвильових процесів в системі “анкер – закріплюючий шар – масив гірських порід”, апробація розробки в умовах шахт і підземних об’єктів цивільного та промислового призначення.

Результати. Встановлено, що вимогам оперативності контролю з можливістю моніторингу геомеханічного стану системи “анкер – закріплюючий шар – масив” найбільш задовольняє ударно-хвильовий метод неруйнівного контролю, що реалізується шляхом нанесення ненормованого удару в торець анкера з реєстрацією та аналізом його коливань, при цьому найбільш інформативним та таким, що задовольняє ергономіці контролю, є параметр – час релаксації, за який амплітуда коливань зменшується в “*e*” разів. Показано, що ступінь защемлення сталеполімерного анкера в масиві та його натяг однозначно впливають на час релаксації затухаючого коливального процесу в системі “анкер – закріплюючий шар – масив”, при цьому зв’язок параметра з защемленням описується обернено пропорційною, а зв’язок з натягом анкера – лінійною залежністю. При ударному збудженні спектральний склад власних коливань клиновидних анкерів залежить як від характеру защемлення, так і від довжини анкера, що дозволяє при контролі виробок ідентифікувати анкери за їх довжиною.

Наукова новизна. Встановлено існування особливого виду затухаючих поздовжніх коливань анкера в пружно-в’язкому середовищі закріплюючого шару. Як інформативний параметр вибрано час релаксації вказаного виду коливань, що в ергономічному діапазоні практично не залежить від сили збуджуючого удару. Встановлено аналітичний зв’язок між інформативним параметром ударно-хвильового методу контролю системи “анкер – закріплюючий шар – масив” і основними показниками якості металополімерного анкерного кріплення гірничих виробок: ступенем зчеплення з масивом та величиною натягу.

Практична значимість. Вдосконалено метод і розроблено апаратуру неруйнівного контролю анкерного кріплення, які дозволяють оперативно у режимі моніторингу оцінювати якість закріплення анкера в масиві та його навантаження в умовах гірничих виробок діючого виробництва, зокрема, і у режимі системного геомеханічного моніторингу стану підземних виробок.

Ключові слова: *гірнича виробка, моніторинг стану, анкерне кріплення, неруйнівний контроль, спосіб, апаратура і методика контролю*

НЕРАЗРУШАЮЩИЙ КОНТРОЛЬ АНКЕРНОГО КРЕПЛЕНИЯ КАК ЭЛЕМЕНТ МОНИТОРИНГА СОСТОЯНИЯ ГОРНЫХ ВЫРАБОТОК

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Цель. Обоснование информативного параметра, разработка способа и аппаратуры неразрушающего контроля анкерного крепления как элементов геомеханического мониторинга состояния горных выработок.

Методика. Аналитические и стендовые экспериментальные исследования ударно-волновых процессов в системе “анкер – закрепляющий слой – массив горных пород”, апробация разработки в условиях шахт и подземных объектов гражданского и промышленного назначения.

Результаты. Установлено, что требованиям оперативности контроля с возможностью мониторинга геомеханического состояния системы “анкер – закрепляющий слой – массив” наиболее удовлетворяет ударноволновой метод неразрушающего контроля, который реализуется путем нанесения ненормированного удара в торец анкера с регистрацией и анализом его колебаний, при этом наиболее информативным и таким, что удовлетворяет эргономике контроля, является параметр – время релаксации, за которое амплитуда колебаний уменьшается в “*e*” раз. Показано, что степень защемления сталеполимерного анкера в массиве и его натяжение однозначно влияют на время релаксации затухающего колебательного процесса в системе “анкер – закрепляющий слой – массив”, при этом связь параметра с защемлением описывается обратно пропорциональной, а связь с натяжением анкера – линейной зависимостью. При ударном возбуждении спектральный состав собственных колебаний клиновидных анкеров зависит как от характера защемление, так и от длины анкера, позволяет при контроле выработок идентифицировать анкеры по их длине.

Научная новизна. Установлено существование особого вида затухающих продольных колебаний анкера в упруго-вязкой среде закрепляющего слоя. В качестве информативного параметра выбрано время релаксации указанного вида колебаний, которое в эргономичном диапазоне практически не зависит от силы возбуждающего удара. Установлена аналитическая связь между информативным параметром ударно-волнового метода контроля системы “анкер – закрепляющий слой – массив” и основными показателями качества металлополимерного анкерного крепления горных выработок: степенью сцепления с массивом и величиной натяжения.

Практическая значимость. Усовершенствован метод и разработана аппаратура неразрушающего контроля анкерного крепления, которые позволяют оперативно в режиме мониторинга оценивать качество закрепления анкера в массиве и его нагружение в условиях горных выработок действующего производства, в том числе и в режиме системного геомеханического мониторинга состояния подземных выработок.

Ключевые слова: *горная выработка, мониторинг состояния, анкерная крепь, неразрушающий контроль, способ, аппаратура и методика контроля*

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