Physical modeling of the rock bolt interaction with the rock massif

Serhii Skipochka[1*], *Oleksandr* Krukovskyi[1], *Viktor* Serhiienko[1], and *Ihor* Krasovskyi[1]

[1]Institute of Geotechnical Mechanics named after M.S. Polyakov of the National Academy of Sciences of Ukraine, Department of Rock Mechanics, 2a Simferopolska St., 49005 Dnipro, Ukraine

Abstract. The results of the physical modeling of the “rock bolt – rock massif” system are presented. The characteristics of rock bolt free oscillations depending on the degree of its clamping and tension were studied on special test benches. Oscillations were caused by a single hit to the rock bolt end. It has been established, that the relaxation time of rock bolt free oscillations is the most informative parameter for non-destructive testing. Experimental dependences, that connect the informative parameter with the characteristics of the rock bolt fastening quality, have been determined. An optimal scheme for registering the oscillations in the “rock bolt – rock massif” system is proposed. The basic data has been obtained to substantiate the method of non-destructive testing the quality of rock bolt fastening.

1 Introduction

Modern anchorage technologies utilize rock bolt fastening along the entire length of the borehole. One of the drawbacks of this technology is difficulty in evaluating the rock bolt fastening quality [1 – 3]. Regulatory recommendations for rock bolt state monitoring provide for the registration of consequences of the unsatisfactory operation of the “support structures – massif” system without identifying its causes. For example, the normative document [4], which regulates the use of resin-grouted rock bolts in coal mines of Ukraine, recommends for monitoring either indicators of tensile forces or depth indicators of radial displacement of mine workings contour. In uncertain situations, destructive rock bolts pull-out tests are carried out in mines conditions. Usually, the main technical control of mining sites with rock bolts consists of a visual inspection [5, 6].

The situation is similar in other countries. For example, the Russian standard [7] generally does not provide for rock bolts monitoring in mines conditions, and the regulatory document [8] regulates the destructive pull-out tests with hydraulic jack for only small selection of rock bolts. Furthermore, in the Kuzbass coal mines, for the visual monitoring of mine roof displacement, roof displacement indicators are used.

Vibro-acoustic method for evaluating the state of the “mine roof – rock bolt” system is used only in some isolated cases [9, 10]. Criteria for a comprehensive assessment of the rock bolt efficiency, based on overall data, are presented in [11].

[*] Corresponding author: skipochka@ukr.net

The existing non-destructive methods for monitoring the rock bolts, developed in countries with developed mining industry, for example [12 – 14], 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 [15, 16]. 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. 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 [17].

Surely, the most objective assessment of the rock bolt efficiency is direct measurements of the fastening strength. However, such measurements are applicable only to an insignificant number of installed rock bolts, and observations of the load dynamics and rock bolt displacement indicators do not allow to evaluate their installation quality at the initial stage of operation. Therefore, development of the methods and means of non-destructive testing, to quickly assess the rock bolt installation quality, is very important task for the mining industry.

2 Methods

Analysis of the oscillatory processes in the "rock bolt – bonding layer – rock massif" system, caused by a single shock pulse, was performed in [18 – 20]. After shock excitation, several types of oscillations arise in the rock bolt, the main of which are longitudinal and bending. With these types of oscillations, nodes exist at clamping points. If the rock bolt is clamped at several points, nodes will also appear at intermediate clamping points, thus creating conditions for the formation of shorter wavelengths. The spectrum will shift to higher frequencies. The denser the clamping points are the more high-frequency components will be in the spectrum. The presence of a special type of longitudinal oscillations of the rock bolt in a viscoelastic medium is explained in [20]. A feature of such oscillations is high initial amplitude. Spectral analysis showed that their main frequency is much lower than for oscillations, caused by the movement of the elastic wavefront in the rod material with multiple reflections from the rock bolt ends. This allows filtering the specified type of oscillations. A wide spectrum of the whole combination of oscillations was experimentally established - from tens of hertz to tens of kilohertz. Informative part of the spectrum is significantly narrower. Approximately, it lies in the range from 0.2 to 1.5 kHz. Therefore, the experimental results were obtained in this frequency range.

Theoretical calculations [20] showed the existence of a deterministic inversely proportional relationship between the parameter p, which characterizes the rock bolt clamping degree, and the free oscillations relaxation time τ: $\tau = B/p$. Here B is a coefficient that characterizes a specific rock bolt.

It is almost impossible to realize the initial state of the rock bolt without minimum clamping $p_{\min}$. Rock bolt even loose contact with supports leads to the outflow of energy into the surrounding space. Therefore, the relaxation time is always the final value, and the clamping degree parameter will be equal to the sum of the current clamping value and initial $p + p_{\min}$. The maximum possible clamping of the rock bolt $p_{\max}$ was taken as the final state of the experiment. The maximum clamping corresponds to the minimum value of the relaxation time $\tau_{\min}$. Rock bolt clamping was described by a dimensionless parameter C, which is equal to the ratio of the initial clamping value to the maximum clamping value ($C = p_{\min} / p_{\max}$). By analogy, to estimate the damping time of the rock bolt oscillations, a dimensionless informative parameter $\tau / \tau_{\min} = \delta\tau$ was introduced. The expression for the relationship between the relative characteristics of the rock bolt clamping and damping of free oscillations is as follows:

$$\delta\tau = \frac{B}{\frac{p}{p_{\max}} + C}. \tag{1}$$

The coefficients B and C are characterize the individual characteristics of the rock bolt and its clamping. They are determined experimentally.

To study the rock bolt free oscillations with different clamping degree, two test benches were made. Their designs are described in [20, 21]. The first test bench – with discrete partial clamping of the rock bolt (Fig. 1).

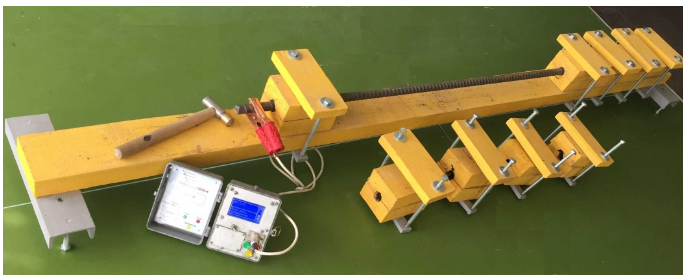

Fig. 1. The test bench for modeling the discrete partial clamping of the rock bolt with the KVAK-4 device.

The base of the test bench is made of wood. To its ends are attached captures with racks located on them. The threaded connection of the struts with pickups allows adjusting the base of the test bench to a horizontal position. A series of supports with linings are laid on the base, creating a clamping section. The supports and the linings are made of wood for better damping. The oval opening in each pair of "support pad" is filled with a resin layer for better adhesion with the ribbed surface of the rock bolt. End and intermediate supports (in quantities up to 14 pcs.), pressure plates and bolts ensure the clamping of a specific part or of the whole rock bolt.

Rock bolt reaction to the external shock excitation with various clamping on both ends of the rod was studied at the first test bench. The oscillations, caused by hammer impact on the rock bolt end, were registered by the special sensor, mounted on the side surface of the rock bolt free part, which is identical to the control in mine conditions. Piezo-ceramic transducers were used as rock bolt oscillations receivers. Initially, the rock bolt is clamped by one section. Clamping $p = p_{\max}$ was achieved with several sections. Their number depended on the rock bolt length.

The second test bench (Fig. 2) was used to study the informative parameter with different clamping and tension of the rock bolt. The real conditions of the rock bolt contact with the rock massif are reproduced on this test bench. The rock mass is modeled by a massive concrete block with a through channel, imitating a borehole. The borehole is divided into 8 identical sections, separated by hermetic partitions, through which the pre-tensioned rock bolt is passed. The rock bolt tension strength was determined using an electronic strain gauge force meter. The change in the rock bolt clamping degree was achieved by filling each section with heated bitumen. Its viscosity parameter stabilization time was four hours. Since the control results depend on the amplitude of oscillations excitation, various forms of shock excitation of the rock bolt were investigated.

Impact force effect on the informative value was determined in a separate experiment. For this, a special hammer with an integrated piezo-accelerometer was used. The impact force was evaluated on an eight-point scale, recorded synchronously with the informative parameter value. To determine the relaxation time (τ) of damped oscillations in the rod, KVAK-4 device was used, which automatically processed the data array within a series of hits. In the experiment, the device worked in the data accumulation mode, processing data, until the specified relative error was achieved. The programmable data processing parameters were as follows: initial sample size – 5; permissible relative error – 5%; fiducial probability – 0.95.

Fig. 2. Second test bench with the pre-tensioned rock bolt.

After each clamping section, the current value of the parameter τ was registered, and then the informative parameter δτ value was determined.

3 Results and discussion

Effectiveness of various methods of oscillations excitation was evaluated on the rock bolt 2.4 m in length, clamped at one end and without preliminary tension. With the constant value of clamping and tension, four options of excitation were used: a hammer with a mass of 0.2 kg (option "a"); a hammer with a mass of 0.5 kg through a hub ("b") and a wooden pad ("c"); a special hammer with a spring-loaded block head ("d"). Statistics of the informative parameter values for various methods of oscillations excitation is given in Table 1.

Table 1. Statistics of the informative parameter τ values with various methods of oscillations excitation.

Statistical characteristics	Excitation option			
	"a"	"b"	"c"	"d"
Value range (min-max)	56 - 68	46 - 56	50 - 64	57 - 67
Average value	62.5	53.1	57.3	63.3
Dispersion	7.8	4.4	16.0	6.8
Medium standard deviation	2.8	2.1	4.0	2.6
Asymmetry	-0.3	-1.0	0.2	-0.7
Variation coefficient $k_{var.}$, %	4.5	4.0	7.0	4.0

Most optimal results were obtained with the hammer 0.5 kg in mass hitting the rock bolt end through a conical hub (variant "b"). On the second place is the special hammer (variant "d", Fig. 3), which is used as a basic tool of excitation, since it allows the user to hit with one hand. This circumstance is a decisive factor when working in mine conditions.

Fig. 3. The hammer with a spring-loaded spherical block head.

Force of impact effect on the informative parameter was evaluated on the rock bolt, fastened on both ends. The rock bolt tension force was 5 and 10 kN. The hammer with a built-in piezo-accelerometer was used in this experiment. Its output was connected to the impact force indicator. The indicator displays eight relative levels of impact force F_r. Level 1 corresponds to very weak exposure, levels 2 and 3 to weak, levels 4 and 5 to medium, levels 6 and 7 to strong, and level 8 to very strong. Relaxation time value τ_0 with very weak force of impact was as initial value. The relative change in the $\delta\tau$ parameter value with force of impact increase was evaluated in the experiment. The results of the experiment are illustrated in Fig. 4.

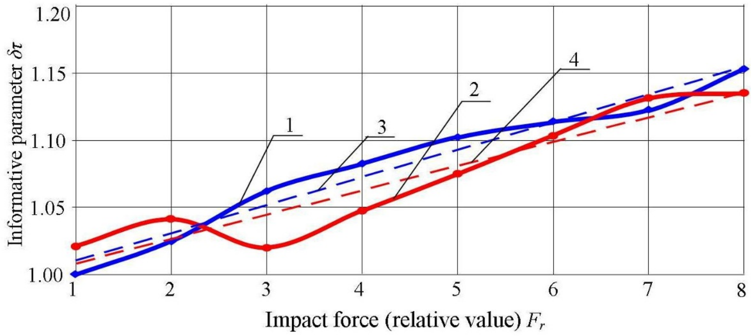

Fig. 4. The informative parameter ($\delta\tau$) dependence on the relative value of the force of impact (F_r) on the rock bolt with tensile force of: 1 – 5 kN; 2 – 10 kN; 3 – trend line for tensile force of 5 kN; 4 – trend line for tensile force of 10 kN.

As can be seen, informative parameter value increases linearly with force of impact increase. However, with the force of impact change over very wide limits, the relative change in the informative parameter was only 15%. With a controlled average force of impact, the instability magnitude can be reduced to a few percent. Additionally, the force of impact stabilizes starting at some value, when the hammer with spring-loaded spherical block head is used. The stabilization threshold is determined by the spring compression degree. It is selected based on average force of impact.

To study the effect of tension force on the damping of oscillations, the rock bolt was clamped at both ends. Then, in the course of the experiment, was subjected to a step by step tension. The rock bolt axial cavity was not filled. This version of the model is adequate to the mechanically anchored rock bolt. The hit was performed with the spring-loaded spherical block head hammer. For each tension value, 3 cycles of the informative parameter definitions were performed, followed by averaging of the data. The rock bolt tension force F_t ration to the change of the informative parameter $\delta\tau$ can be approximated by a linear function: $\delta\tau = 1 - kF_t$ ($R^2 = 0.95$). The function graph is presented in Fig. 5.

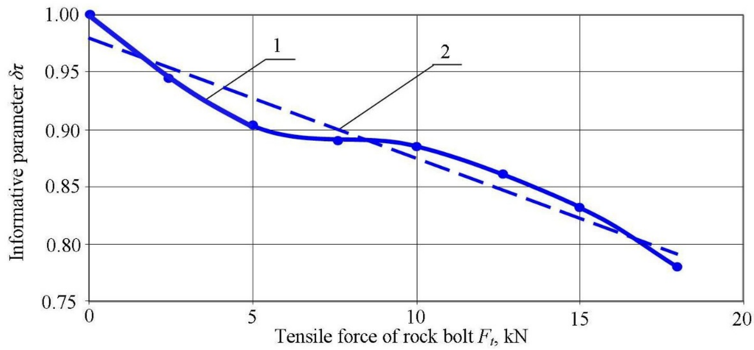

Fig. 5. The rock bolt tension force F_t ration to the change of the informative parameter δτ: 1 – experimental dependence, 2 – linear approximation.

The effect of the clamping degree on the informative parameter, depending on the rock bolt length, was also researched at the first test bench (Fig. 1). The research results are presented in Fig. 6. As can be seen, the rock bolt length effect on the value of the informative parameter is insignificant and manifests itself only when the rock bolt is poorly clamped. It is expected, that, in the real conditions, the rock bolt length effect on the indications of the device will be comparable with the parameter definition error.

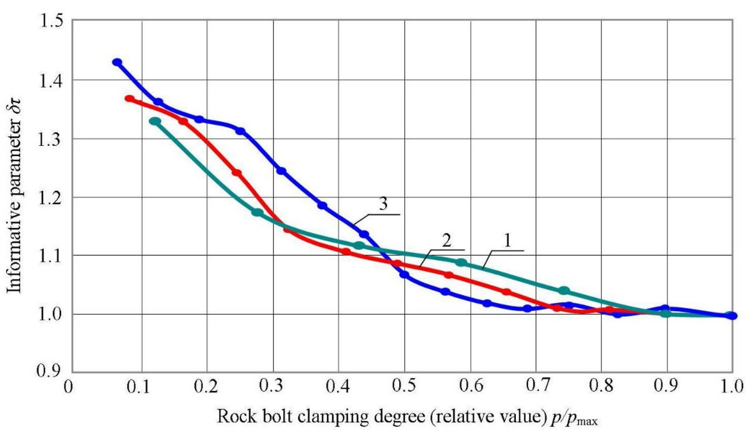

Fig. 6. The informative parameter ratio to the relative clamping magnitude of various lengths rock bolts: 1 – 1.2 m, 2 – 1.8 m, 3 – 2.4 m.

Coefficients values in the analytical expression (1), that links the informative parameter with the clamping degree of various lengths rock bolts, are given in Table 2.

Table 2. The coefficients values in the formula, that links the informative parameter with the clamping degree of various lengths rock bolts.

Rock bolt length, m	Coefficient *B*	Coefficient *C*
1.2	4.28	3.28
1.8	2.65	1.85
2.4	2.29	1.60

The experiment at the second test bench was more complex. Before filling the sections, the 2.4 m long rock bolt was tensioned with a force of 18 kN. Both ends of the rock bolt were clamped before the sections were filled. After filling all sections with hardening material, it was discovered, that the initial value of the relaxation time τ_0 is 1.42 times its final value τ_{min}. In accordance with Fig. 6, the estimated initial clamping p_0 / p_{max} in relative terms is 0.08. The interval between this value and the final value, equal one, is realized by successfully clamping the rock bolt in each of the eight sections.

The informative parameter values dependence to the clamping degree of tensioned rock bolt is shown in Fig. 7. The dependence is approximated by a function (1) with the coefficients: $B = 3.46$, $C = 2.41$.

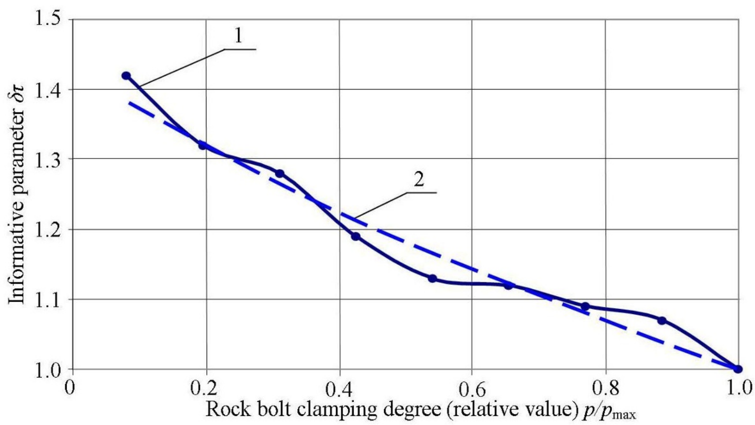

Fig. 7. Relaxation time relative values ratio to the tensioned rock bolt clamping degree relative values: 1 – experimental values, 2 – approximating curve.

4 Conclusions

Physical modeling of oscillatory processes in the rock bolt, depending on its clamping and tension, has shown the fundamental possibility to create a method and device for non-destructive testing of rock bolt fastening. It has been proven, that the use of the relaxation time of a damped oscillations as an informative parameter of non-destructive testing has several advantages. These include: a wide dynamic range of the signal, reducing the requirements for the stability of the impact force and the quality of the receiver acoustic contact with the rock bolt; ease of measuring the time interval and the representation of this parameter in digital form; low power consumption of the device.

The theoretically obtained [20] inversely proportional dependence of the relaxation time of the rock bolt oscillations on its clamping degree has been experimentally confirmed. It has been shown, that by the proposed method, the rock bolt fastening in a rock massif with high reliability is controlled in the range from the minimum to 60% of the maximum possible. With a further clamping degree increase, value of the informative parameter varies within the error of definition.

Insignificant increase of the informative parameter value with force of impact increase has been discovered. The special design hammer with wide range stabilization of the force of impact has been proposed.

A linear reduction of the relaxation time of the rock bolt free oscillations with its tension force increase has been established.

The main reason for the device readings variations lies in the complex spectral composition of the oscillations. The characteristics of the attenuation process are maintained for one frequency prevailing in the spectrum. The simultaneous presence of other frequencies with random phases and amplitudes gives unpredictable deviations that are not repeated in a series of consecutive measurements. For the same reason, informativeness of non-destructive control decreases with increase of the rock bolt clamping.

The obtained initial data are the basis for the method improvement and equipment modernization for non-destructive testing of rock bolt fastening.

The work results are part of the “Promoting the development of priority research areas” (KPKVK 6541230) research under National Academy of Sciences of Ukraine funding program.

References

1. Salcher, M., & Bertuzzi, R. (2018). Results of pull tests of rock bolts and cable bolts in Sydney sandstone and shale. *Tunnelling and Underground Space Technology*, (74), 60-70. https://doi.org/10.1016/j.tust.2018.01.004
2. Blanco-Martín, L., Tijani, M., Hadj-Hassen, F., & Noiret, A. (2013). Assessment of the bolt-grout interface behaviour of fully grouted rockbolts from laboratory experiments under axial loads. *International Journal of Rock Mechanics and Mining Sciences*, (63), 50-61. https://doi.org/10.1016/j.ijrmms.2013.06.007
3. Kang, H., Yang, J., & Meng, X. (2015) Tests and analysis of mechanical behaviors of rock bolt components for China’s coal mine roadways. *Journal of Rock Mechanics and Geotechnical Engineering*, 7(1), 14-26. https://doi.org/10.1016/j.jrmge.2014.12.002
4. SOU 10.1.05411357.010:2014. (2014). *Systema zabezpechennia nadiinoho funktsionuvannia hirnychykh vyrobok z ankernym kriplenniam. Zagalni tekhnichni vymohy.* Kyiv: Minenerhovuhillia Ukrainy.
5. Bondarenko, V., Kovalevs’ka, I., Svystun, R., & Cherednichenko, Y. (2013). Optimal parameters of wall bolts computation in the united bearing system of extraction workings frame-bolt support. *Annual Scientific-Technical Collection – Mining of Mineral Deposits*, 5-9. http://dx.doi.org/10.1201/b16354-3
6. Kovalevska, I., Symanovych, G., & Fomychov, V. (2013). Research of stress-strain state of cracked coal-containing massif near-the-working area using finite elements technique. *Annual Scientific-Technical Collection – Mining of Mineral Deposits*, 159-163. http://dx.doi.org/10.1201/b16354-28
7. GOST R 52042–2003. (2004). *Krepi ankernye. Obshchie tekhnicheskie usloviya.* Moskva: Izdatel’stvo standartov. RF.
8. VSN 126–90. (1991). *Kreplenie vyrabotok nabryzgbetonom i ankerami pri stroitelstve transportnykh tonneley i metropolitenov.* Moskva, RF.
9. Skipochka, S.I., Palamarchuk, T.A., Mukhin, A.V., & Chervatuk, V.G. (2002). Vibroakusticheskiy control’ dinamiki sistemy “ugleporodnyy massiv – krep’ gornykh vyrabotok”. *Geo-Technical Mechanics*, (36), 131-135.
10. Ivanovic, A., & Neilson, R. D. (2008). Influence of geometry and material properties on the axial vibration of a rock bolt. *International Journal of Rock Mechanics and Mining Sciences*, *45*(6), 941-951. https://doi.org/10.1016/j.ijrmms.2007.10.003
11. Vinogradov, V.V., & Adorskaya, L.G. Sistema monitoringa gornykh vyrabotok s oporno-ankernoy krep’yu (2002). *Geo-Technical Mechanics,* (38), 29-41.
12. Gale, W.J., Mark, C., Oyler, D.C., & Chen, J. (2004). Computer Simulation of Ground Behaviour and Rock Bolt Interaction at Emerald Mine 2004. *Proc. 23rd Intl. Conf. on Ground Control in Mining.* Morgantown, West Virginia University, 27-34.
13. Madenga, V., Zou, D.H., & Zhang, C. (2006). Effects of curing time and frequency on ultrasonic wave velocity in grouted rock bolts. *Journal of Applied Geophysics*, *59*(1), 79-87. https://doi.org/10.1016/j.jappgeo.2005.08.001

14. Shi, Z.M., Liu, L., Peng, M., Liu, C.C., Tao, F.J., & Liu, C.S. (2018). Non-destructive testing of full-length bonded rock bolts based on HHT signal analysis. *Journal of Applied Geophysics*, (151), 47-65. https://doi.org/10.1016/j.jappgeo.2018.02.001
15. Voznesenskiy, E.A. (2007). Identifikatsiya defektnykh ankerov podzemnykh vyrabotok putem analiza arusticheskogo otklika. *Collection of works of the XIX session of the Russian Acoustical Society.* Moskva: GEOS, (1), 365-369.
16. Voznesenskiy, A.S., Koryakin, V.V., & Voznesenskiy, E.A. (2016). Physico-technical evaluation of shock response spectrum method for strata bolting control. *Gornyi Zhurnal*, *2224*(3), 17-20.
17. Blahut, R.E. (2010*). Fast Algorithms for Signal Processing*. University of Illinois, Urbana-Champaign. https://doi.org/10.1017/CBO9780511760921
18. Skipochka, S.I., Serhiienko, V.N., & Krasovskyi, I.S. (2017). Rationale of mounting quality control parameters for anchors in rocks by vibroacoustic method. *Metallurgical and Mining Industry*, *304*(1), 106-110.
19. Skipochka, S.I., Sergienko, V.N., & Krasovskiy, I.S. (2018). Rationale of improved method of anchorage impact-wave control. *Up-to-date resource- and energy-saving technologies in mining industry*, *21*(1), 47-55.
20. Skipochka, S., Krukovskyi, O., Serhiienko, V., & Krasovskyi, I. (2019) Non-destructive testing of rock bolt fastening as an element of monitoring the state of mine workings. *Mining of Mineral Deposits*, *13*(1), 16-23. https://doi.org/10.33271/mining13.01.016
21. Skipochka, S.I., Serhiienko, V.N., & Krasovskyi, I.S. (2018). *Sposib kontroliu yakosti zakriplennia ankernoho stryzhnia v sverdlovyni*. Utility Patent No. 122418, Ukraine.