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SCIENCE AND PRACTICE FOR ASSESSING THE STATE OF UNDERGROUND STRUCTURES SUPPORT BY VIBROACOUSTIC METHOD

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Abstract

In this work, subject of the research is a method of non-destructive vibroacoustic control of underground structures support. The purpose of the research was to create a methodology and apparatus for vibroacoustic control of the state of the system "support – rock massif" with a wide range of use. The main types of objects where the use of this method is appropriate are determined. Negative influence of external factors on performance characteristics of support is shown. A basic type of support for underground objects is reinforced concrete. It is established that the most characteristic defects are formation of cavities in geological environment behind the support and broken connection of separate segments of the support. The influence of these defects on character of free oscillations of support elements at single shock action was studied theoretically. It is established that the following parameters can be informative for detecting these defects: amplitude characteristic of package of vibration, its duration and spectral composition. Information about the means of vibroacoustic control designed by the Institute with participation of the authors is provided. The methodical features of using vibroacoustic control for assessing technical state of different types of support are considered. The limitations for using the method are explained. Some results of the use of vibroacoustic control of support in underground objects of the various purposes are given.

Keywords: underground structure support, non-destructive control, vibroacoustic method, free oscillations, informative parameters, technical state

Introduction

In Ukraine, the use of underground space is developed in several directions. The first of them is related to mineral mining. The second direction consists in construction of underground structures for special purpose, for example, transport and hydro-technical tunnels, dock parts of the pumping stations, etc. The third direction is the alternative use of underground space for the objects that could be located on the earth surface. In particular, this applies to specific productions, for example, vine-making enterprises. This category also includes underground storage facilities, underground reservoirs for oil fuel. Accelerated development of building of objects exactly of this category is particularly important for Ukraine, taking into account a specific situation in the country. Underground construction, regardless of its functional purpose, is influenced by external geological environment. Support of underground structures is oriented on resistance to rock pressure. In some cases it must also provide waterproofing. The necessity to maintain operating state of the mine workings depends on their purpose and can last from a few months to many years. Other underground objects can assume long-time exploitation - for tens of years. Safe operation of workings is largely determined by technical state of their support required its periodic control. Traditional type of control is visual inspection with documenting of the detected defects. However, certain category of defects cannot be detected in this way. In particular, it applies to cavities in massif on the contact with the capital support. Their presence results in redistribution of stresses in the safety structure and causes its further deformation. In addition, cavities accumulate underground water and, in case of broken impermeability of the shell of the underground structure, become a source of filtration. The pressing task is to detect them timely with the use of methods of non-destructive control.

An effective modern method for detecting cavities behind the support is underground radar [1,2]. However, its use is associated with certain limitations:

- the need for direct access to the controlled surface;
- the impossibility to control rock massif when support with high electrical conductivity (concrete covered with a metal sheet, cast iron tubing, reinforced concrete with a large concentration of reinforcement) is used.

Other factors also play a certain role: significant cost of georadars and the need to attract highly qualified specialists.

There is also a problem that concerns support made of separate segments. Ideally, each of them should be able to withstand the load in accordance with the design solutions. Broken mechanical connection between the elements of support due to the destruction of the seams causes their uneven loading. Visual inspection detects only the consequences of underground structure operation in this mode - in the form of deformed elements. Timely obtained information on the distribution of stresses in the support makes it possible to significantly reduce the cost of preventive maintenance works.

The purpose of the research was to create a methodology and equipment for non-destructive control of the state of the system "support - rock massif" at objects with a wide scope of use. The benchmarks were: low cost of equipment and ease of use.

Analysis of other sources and the results of our own researches show that the goal can be achieved by using the vibroacoustic method [3-5]. The development of different variants of control is provided for the wide variety of possible objects, where support characteristics and control conditions differ significantly.

Theoretical justifications of variants of the method

A common cross-sectional shape of underground objects is a ring. An example can be vertical mine shafts, as well as some variants of horizontal and inclined hydro-technical tunnels. Support is mainly concrete or reinforced concrete. It is made in the form of separate sections, the seams between which are sealed. A fragment of the support in contact with the external environment is presented in Fig. 1.

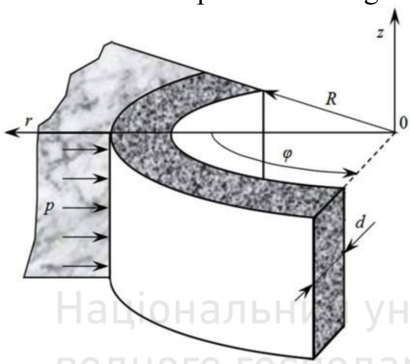

Fig. 1. Fragment of the ring support of the underground structure

The geometric characteristics of support are characterized by an internal radius *R* and thickness *d*. The hypothesis of a thin homogeneous shell is accepted. This is true if $d \ll R$. The second precondition is that the height of the section also significantly exceeds the thickness of the shell. This makes it possible to consider the problem in a flat formulation (in the cross-sectional plane).

The oscillations in the shell are excited by applying a point shock to it from the internal space of the structure. The interaction of the shock devices with the support material is considered absolutely elastic. Energy losses in the shell material associated with the viscosity of the material are not taken into account. The reaction of the environment to the radial deformations of the shell areas is represented by a uniform pressure *p*. To analyze the free oscillations in the shell, in addition to the geometric characteristics of the support, information on the physical and mechanical properties of the shell material and the environment is necessary. The list of characteristics and their symbols are given in Table. 1.

Table 1

Physical and mechanical characteristics of the elements
of the mathematical model «support – environment»

Name of physical parameter	Dimension of parameter	Symbol of material	
		of support	of environment
Density	kg/m^3	ρ_1	ρ_2
Modulus of elasticity in tension or compression	Pa	E_1	E_2
Shear modulus	Pa	G_1	G_2
Dynamic viscosity	Pa·s	η_1	η_2
Longitudinal wave speed	m/s	c_1	c_2
Dynamical Poisson's ratio	-	ν_1	ν_2

To analyze the behavior of ring-shaped structures under static or dynamic load, there is a special characteristic - cylindrical rigidity, denoted by the symbol *D*

$$D = \frac{E_1 d^3}{12(1-\nu_1^2)}. \tag{1}$$

To simplify analytic expressions, an additional function Ψ is also introduced, which is associated with the current radial coordinate *r* and the angular coordinate of the *φ* in the cross-sectional plane. It is determined by a system of equations

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$$r = \nabla^4\Psi; \quad \varphi = Ed\nabla^2\Psi. \tag{2}$$

The key point is to take into account resistance of the external environment. This problem for cylindrical shells is described in detail in the works [6-8]. To understand the essence of physical processes, in our case, it is enough to accept simplified boundary conditions. The instantaneous resistance value *p* for a small area of the surface of the shell has three components:

- hydrostatic pressure at depth *H*

$$p_1 = -\rho_2 g H; \tag{3}$$

- elastic resistance from the environment

$$p_2 = -\frac{k_e \rho_2 c_2 \partial r}{\partial t}; \tag{4}$$

- viscous resistance from the environment

$$p_3 = -\frac{k_v \eta_2 \partial r}{\partial t}. \tag{5}$$

The k_e and k_v parameters in the formulas (4) and (5) are the proportionality coefficients.

Given that the shell is quite thin, and the main oscillation frequency is low, we can neglect the difference in the oscillation phases along the radial coordinate in the shell material. Then the instantaneous balance of stresses in the shell area caused by the shock is balanced by instantaneous resistance of the external environment

$$\frac{12}{d^2}(1-\nu_1^2)\nabla_k^2(\nabla_k^2\Psi)-\rho_1 d\frac{\partial^2 r}{\partial t^2}=\sum_{i=1}^{3}p_i \quad . \qquad (6)$$

The total resistance of the external environment is defined as

$$\sum_{i=1}^{3}p_i=-\rho_2 gH-(k_e\rho_2 c_2++k_v\eta_2)\frac{\partial r}{\partial t} \quad . \qquad (7)$$

Equation (6) describes several types of oscillations defined by the index *k*. In particular, the set of frequency components of radial displacement in the cross-sectional plane is described by the following equation

$$\Delta r_n(t)=\Delta r_0 e^{-\delta_n t}\cos(\omega_n t+\theta_n)+C, \qquad (8)$$

where Δr_0 - initial deflection of the shell after shock; Δr_n - spectral components of the instantaneous deflection of the shell; δ_n – attenuation coefficient of spectral components; ω_n – circular frequencies of the spectrum components; θ_n – initial phase shifts; *C* – constant deformation caused by hydrostatic pressure.

The value of attenuation coefficient for the frequency component is determined by the equation

$$\delta_n=k_n(k_e\rho_2 c_2+k_v\eta_2). \qquad (9)$$

where k_n are the coefficients of proportionality.

In most cases, the cavity is filled with a liquid mix of water with soil. This mix has a much lower density and viscosity than the natural massif. Accordingly, in the areas of the cavities, the attenuation coefficient for both individual spectral components and for a package of oscillations as a whole is significantly reduced. This means an increase in the duration of the oscillatory process and an increase in the average amplitude of oscillation.

Underground structures with a rectangular cross-section are also common. Their support is made mainly in the form of a set of reinforced concrete slabs, between which there are tight seams. The design condition of the plate assumes its strong mechanical connection with adjacent elements along the contour. One of the defects is the destruction of the seams. In addition to the possible filtration of water in the underground structure, it reduces the stability of support. The illustration to the mathematical model of support of reinforced concrete slabs is presented in Fig. 2.

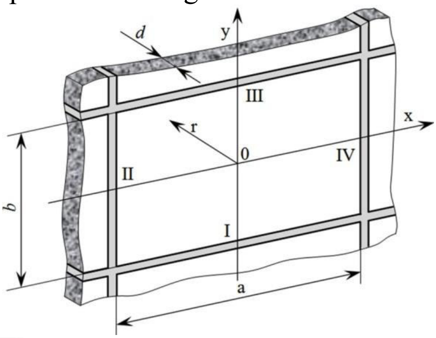

Fig. 2. Fragment of support with reinforced concrete slabs

By analogy, let's consider the simplified model of occurrence of free oscillations in a thin plate. More detailed analysis of this process is shown in literature [9,10]. When impacting on the central part of the plate, there is a damped oscillating process, which is described by the equation

$$\frac{Ed^3}{12(1-\nu^2)}\left(\frac{\partial^4 r}{\partial x^4}+2\frac{\partial^2 r}{\partial x^2}\cdot\frac{\partial^2 r}{\partial y^2}+\frac{\partial^4 r}{\partial y^4}\right)=p. \qquad (10)$$

As in the previous case, the general solution of the equation (10) can be represented in the form (8) as a set of damped oscillations with different frequencies, and a constant component. The value of the basic frequency of oscillations and corresponding harmonics depends significantly on the boundary conditions. Two extreme idealized cases are considered for each side of the plate:

- prohibition of deformation in case of high quality seam;
- lack of stresses on the corresponding side of the plate when the seam is completely destroyed.

Four variants of clamping the sides of the plate are considered. Each of them has an expression to evaluate the value of the main cyclic frequency ω_1 of free oscillations. Due to the fact that the viscosity of the environment in contact with the plate is not taken into account, the assessment is just of qualitative nature. The results are given in Table 2.

Table 2

Calculation of indicative values of the basic frequency of free oscillations of the plate for different conditions of its fixing along the contour

Destroyed seam	Monolithic seam	The main frequency of free oscillations
-	I,II, III, IV	$\omega_1 = 11.18d\sqrt{\frac{E_1}{3\rho_1(1-\nu_1^2)}\left(\frac{1}{a^4}+\frac{0.605}{a^2b^2}+\frac{1}{b^4}\right)}$
I, II	III, IV	$\omega_1 = 7.71d\sqrt{\frac{E_1}{3\rho_1(1-\nu_1^2)}\left(\frac{1}{a^4}+\frac{1.115}{a^2b^2}+\frac{2.441}{b^4}\right)}$
II, IV	I, III	$\omega_1 = 4.98d\sqrt{\frac{E_1}{3\rho_1(1-\nu_1^2)}\left(\frac{1}{a^4}+\frac{2.566}{a^2b^2}+\frac{5.138}{b^4}\right)}$

According to the results of mathematical modeling, the tendency of reduced main frequency of the plate free oscillations is visible with deterioration of its mechanical contact with adjacent support elements. At shock excitation of area of support with a weak mechanical connection to adjacent elements and the surrounding massif, mechanical energy is largely localized in the volume of the slab itself. Due to this, duration of the oscillatory process increases and its integral amplitude characteristic increases. Increasing the stability of the plate is associated with an increase in energy outflow due to a qualitative mechanical connection with other elements on all surfaces except the internal. This drastically reduces the quality factor of the oscillatory system and causes a rapid decrease in the amplitude of all spectral components.

Technical means to implement the method

Serial technical means of vibroacoustic diagnostics are mostly passive recorders of vibration that occurs during continuous operation of mechanisms [11-14]. The method of spectral analysis is mainly used to identify and determine the nature of defects. Massive concrete and reinforced concrete structures can be diagnosed by the passive method only in some cases. In particular, this is possible, for example, when assessing the state of the bridge structures at the time of train movement [15]. The [16] describes the methodology and the results of the assessment of the state of building structures by determining the parameters of their vibration during the movement of urban transport. A similar approach is considered as one of the variants of vibroacoustic control of the state of concrete pavement [17]. In most cases, this technique cannot be applied for assessing the state of underground structures support.

Active vibroacoustic diagnosis involves forced excitation of the controlled object. Given the large mass of structures, their continuous excitation is energy expensive. However, it is sometimes used when using serial equipment for spectral signal analysis. The [18] describes the use of a perforator as an oscillation exciter.

Single shock excitation of structures is more widely used. The [19] describes the experience of inspecting of support in Japan tunnels with a hammer. In the simplest version, this assumes identifying the defects by ear by experienced operator. There is also information about modern control technologies: the use of a robotic complex with stable shocks, automated registration and signal processing using artificial intelligence technologies.

Studies of the authors [20] found that the most sensitive characteristic in the use of the vibroacoustic method is the amplitude of free oscillations. But at the same time, the value of this informative parameter is significantly influenced by the impact force and the conditions of contact of the vibration receiver with the surface of the structure. The problem of impact force is partially solved by the use of an accelerometer that is rigidly connected to the shock device. Numerical value of the informative parameter should be adjusted according to the magnitude of the output signal of the accelerometer. The disadvantage of this technical solution is the presence of an additional cable that connects the shock device to the electronic unit. The authors have developed a simple shock device where the residual impact energy is absorbed by a pre-compressed spring. The design of the device is presented in Fig. 3.

The massive metal case 1 is rigidly connected to the wooden handle 2 by retainer 3. Spring 4 and ball 5 are located in the cylindrical recess of the case 1. Their working position is fixed with a nut 6. The point of impact is the spherical surface of the ball. Thanks to the pre-compressed spring, with a low impact force, the design responds to contact with the surface as a whole.

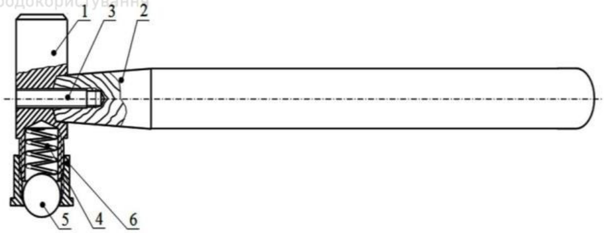

Fig. 3. Structure of the shock device: *1* – case; *2* – handle; *3* – retainer; *4* – spring; *5* – ball; *6* – nut

When the impact force exceeds the resistance of the compressed spring, it is compressed additionally, absorbing the excess energy of the impact. By selecting the value of the previous compression of the spring and training the operator, we managed to achieve quite stable parameters of the impact.

To increase stability of the contact receiver of the vibration, the following improvements were performed:

- a conical concentrator is used for point contact of the receiver with the control object;

- the performance of the device is ensured only when the pressure is achieved to the controlled surface)

The implementation of this technical solution is illustrated in Fig. 4.

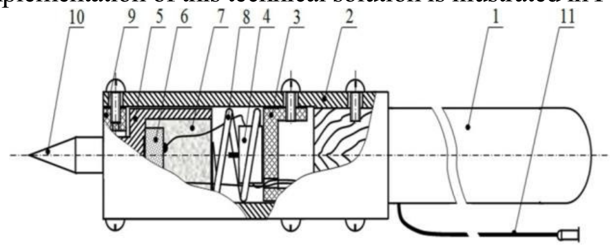

Fig. 4. Design of the contact receiver of the vibration of support: *1* – wooden rod; *2* – case; *3* – support; *4* – micro-switch; *5* – insert; *6* – piezoceramics; *7* - layer of compound; *8* – spring; *9* – cover; *10* – conical concentrator; *11* – cable with a connector

On the wooden rod *1*, there is a metal cylindrical case *2*, in which support *3* is rigidly fixed. It is installed with a micro-switch *4* with normally open contacts. Metal cylindrical insert *5* can limit its movement along the case *2* axis. In the deaf opening of the insert, there is a piezoceramics *6*, which is fixed with a layer of compound

7. There is a compression spring between the support *3* and the insert *4*. At the end of the case *2*, cover *9* is rigidly fixed.

The end of the insert *5* with a conical concentrator *10* passes through the hole in the cover. Cable 11 with a connection is designed for electrical connection of piezoceramic to electronic block.

In the non-working position, the insert *5* with the help of spring *8* is pressed against the cover *9*.

The contacts of the micro-switch *4* are open. The primary vibration converter in the form of piezoceramics is not connected to the input of the electronic block.

When conical concentrator presses on the controlled surface with the required force, spring *8* is compressed. This causes the closure of micro-switch *4* and provides electrical connection of piezocerams to the electronic unit. In some variants of the equipment, the power supply of the equipment is closed.

This significantly increases its efficiency. It is established that the minimum pressure required for establishing a stable acoustic contact of the sensor with a controlled surface is about 30 N.

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One of the tasks of the research was to create the most simple and cheap means of control. From the point of view of hardware implementation, the simplest of the possible physical parameters is to determine the period of time [21].

The relevant informative parameter is the duration of the oscillation process damping to a threshold value. This principle is used in the work of equipment DYKON and SHVK [22] developed by the authors of this work. The exterior view of the electronic blocks of the mentioned means of control is presented in Fig. 5.

The threshold, which determines the end of oscillations analyzing, is fixed. Therefore, numerical value of the duration of the oscillation process, additionally to oscillation characteristics, depends on the initial amplitude as well. For its stabilization, the described devices for excitement and registration of oscillations were used. On the basis of the experience of these technical means operation, a more sophisticated vibroacoustic equipment of the KVAK was developed to control the state of anchorage and reinforced concrete support [23].

a *b*

Fig. 5. Means of vibroacoustic control with determining the duration of free oscillations: *a* – DYKON, *b* – SHVK

The informative parameter is the time of free oscillations relaxation. The choice of this parameter complicated the data processing process, but increased the reliability of the results. The value of relaxation time in a wide range of changes in the level of the input signal does not depend on its initial amplitude. The accuracy of the results is also increased by prompt statistical processing of data with multiple controls at one point. This provides automatic screening of the anomalous values for this sample and the statistical assessment of the accuracy of the result.

In addition to controlling the state of support elements, the assessment of the strength of the anchors is also monitored. The exterior view of the equipment with a set of peripheral devices is presented in Fig. 6.

a *b*

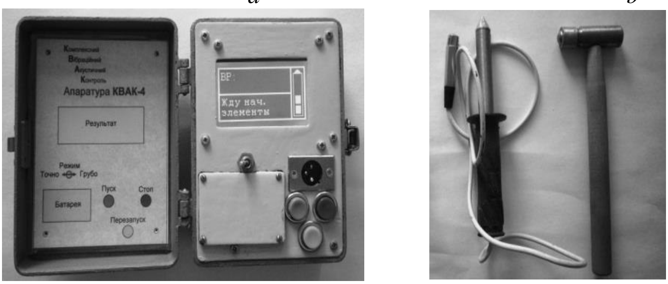

Fig. 6. Exterior view of equipment KVAK-4: *a* – electronic block, *b* – shock device and vibration receiver

The recent clear tendency is to create means for vibroacoustic control of building structures, including support elements, based on the spectral analysis of a package of damped vibrations [24,25]. The main advantage of this variant is weak dependence of control results on the level of the input signal and its high informativeness.

The classic variant of the modern approach is the conversion of the signal into a digital form and its subsequent processing by software tools. Designed with the participation of the authors, the equipment ISK refers to the previous generation, where the analysis of the spectrum of one signal is carried out by means of technical solutions. It is a ten-lane analog spectrum analyzer of parallel type with a range from 31,5 Hz to 16000 Hz [26]. The equipment is made in the flameproof design. This makes it possible to use it in coal mines that are hazardous by gas and dust.

The exterior view of the equipment ISK complete with peripheral elements is presented in Fig. 7.

a *b*

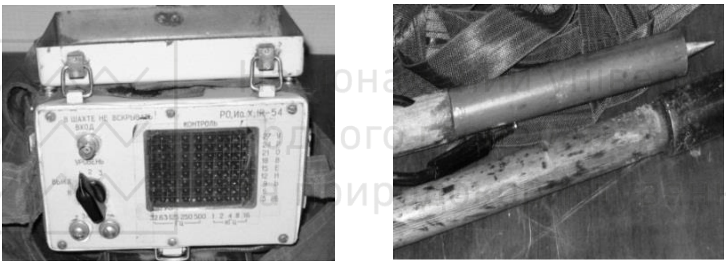

Fig. 7. Exterior view of equipment ISK: *a* - electronic block, *b* - shock device and vibration receiver

Methodical features of vibroacoustic control of support

The most convenient objects for vibroacoustic control are long underground structures with the same characteristics of support along the entire length. A favorable factor in controlling such structures is that there is no equipment and engineering communications. A typical example is some hydro-technical tunnels. The main part is usually fixed with reinforced concrete in the form of separate sections. Cross-sections for control are agreed with stakes. In their absence, the marking is made along the axis of the structure. The recommended step is 2 m. The control points in the cross-section are arranged with taking into account the position of the individual support sections. If possible, the points along the contour should be distributed evenly. The plots with variable thickness of the support are not controlled because they are characterized by other features of free oscillations. Control points are the points to apply mechanical shock. Examples of their placement are shown in Fig. 8.

Vibration reception points are located at a height which is much greater than the thickness of the shell. Three measurements should be taken at each point. The result is averaged.

Fig. 9 illustrates the performance of vibroacoustic diagnostics.

The peculiarity of vibroacoustic control, regardless of the choice of technical means, is the dependence of the informative parameter on the support characteristics.

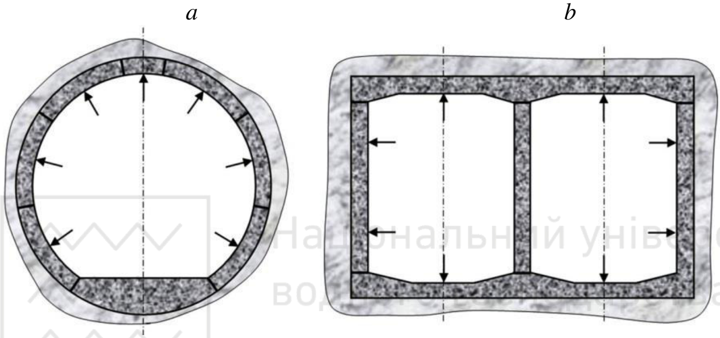

Fig. 8. Location of shock points in the cross-section of the support: *a* – in the underground part of the Dnipro-Ingulets channel, *b* – on the site of the sewer collector in the city of Dnipro

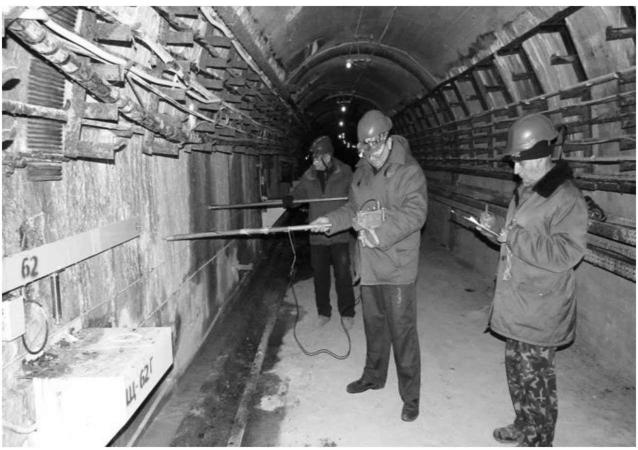

Fig. 9. Performing vibroacoustic diagnostics in the upper footway of Dnipro hydroelectric station

To determine of the technical state of the support elements of a certain size and shape, control is performed in areas where the state is established by direct methods such as control drilling.

The desired volume of samples in areas with quality and clearly defective support should satisfy the condition of the correct statistical processing (at least 30 definitions). The hypothesis of the normal nature of the distribution of values of the informative parameter in both samples with average p_n values for quality support and p_d for defective support is accepted.

The variation of values is determined by two factors: error of determining the informative parameter and features of a specific support point. If the presence of a defect causes an increase in the value of the informative parameter, then, according to the 3σ rule, the range from the minimum value to $p_n+3\sigma$ corresponds to the quality support.

Similarly, values exceeding $p_d-3\sigma$ are suspicious for a defect. Possible distribution of values of the informative parameter is illustrated in Fig. 10.

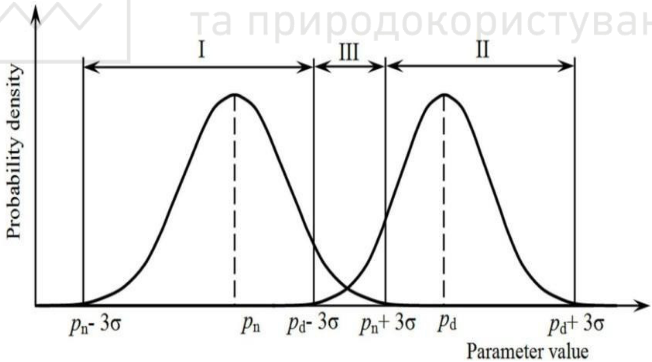

Fig. 10. Distribution of values of informative parameter in control of support of different quality

Regardless of the choice of informative parameter and means of control, its informativeness sharply decreases with the growth of the thickness of the shell (Fig. 11). In accordance with Fig. 11, three ranges of the thickness of the shell with different efficiency of vibroacoustic control are determined.

When the shell thickness is less than d_1, probability to detect defects is very high. In the thickness range from d_1 to d_2 , data distribution graphs for quality and defective supports are approaching. The width of the uncertainty zone becomes too large. With thickness values more than d_2, control becomes impossible at all.

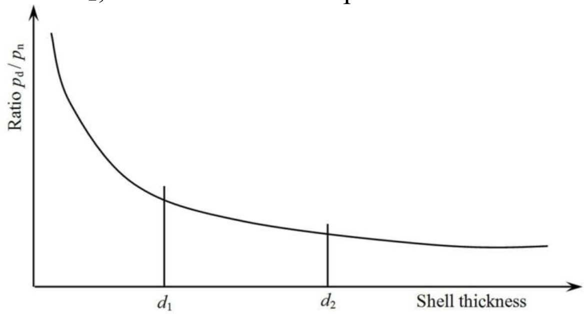

Fig. 11. Decrease of the information content of vibroacoustic control with an increase in the thickness of the shell

Practical experience showed the limit for the probability of detecting the cavity. It is a maximum support thickness 0.8–1.3 m depending on the type of support, variant of the method and characteristics of the equipment. The thickness of many reinforced concrete structures ranges from 0,5 m to 0,8 m, i.e. corresponds to the conditions of significant uncertainty of control results. In this case, the following measures are taken to increase the accuracy:

- to condense the control grid;
- to increase number of measurements at one point of control;
- to divide the obtained range of values by a certain number of gradations (from 6 to 10).

Then, by using automatic programs of isolines construction, the inner surface of the structure is scanned with displayed gradations. This map should be considered as a prognostic one, where areas of different probability of defects are shown with corresponding number of gradations. According to Fig. 11, for very thin shells, the informativeness of the vibroacoustic control is extremely high. An example of such a shell is a layer of shotcrete applied to the surface of the massif. The great difference in the value of the informative parameter for quality and defective areas of the coating allows establishing the presence of cavities behind the shell without preliminary calibration, and outlining them in details. This provides a special variant of the method, the scheme of which is presented in Fig. 12.

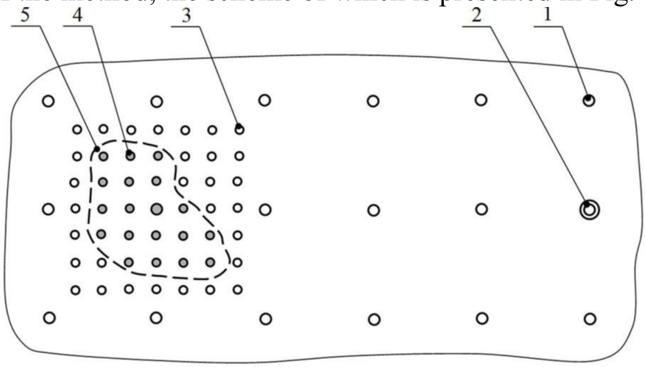

Fig. 12. The scheme of detection of the cavity under very thin shells: *1* – basic control points; *2* – point of reception of vibration; *3* – points with condensed grid of control; *4* – points with abnormal values of informative parameter; 5 – contour of the defective zone

Detection and control of a cavity is performed in two stages. The first performs control with the use of methods described earlier using points *1* of the base grid. If an anomalous value is found at one point, the vibration receiver is fixed at point *2* at such a height from it, which is several times greater than the step of control. The operator stimulates the vibration in the area of the potential cavity on the condensed grid in point *3*. Points *4* are singled out, the impact to which leads to anomalous values of the informative parameter. Due to the distant point of registration of vibration, the change in the distance between the excitation points and reception of vibration affects the result of the control much less than the difference between the contact of the shell with the adjacent environment. The defective area is determined directly at the site of the inspection without intermediate data processing.

Examples of the use of vibroacoustic control of underground structures support

An example of a long underground structure with reinforced concrete support is the sewer collector in the city of Dnipro. The cross-section of the collector is shown in Fig. 8b. The support is made in the form of reinforced concrete slabs with a thickness of 0.3 m.

Characteristic defects are cavities behind the shell and the destroyed seams between the plates (Fig. 13).

Fig. 13. The destroyed seams between individual slabs of support of sewer

The joint influence of both types of defects is reflected in the scan of the collector fragment (Fig. 14).

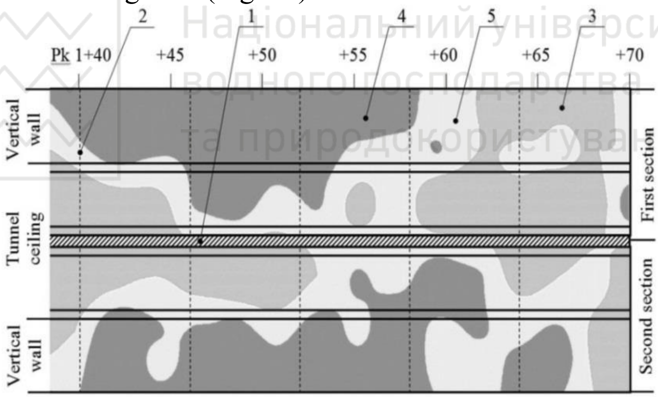

Fig. 14. A scan of a sewage collector fragment with the results of vibroacoustic diagnostics: *1* – the inner partition between sections; *2* – a seam between the mounting elements; *3* – areas with the absence of cavities behind shell; *4* – areas of the cavities behind shell; *5* – areas with intermediate state

The control of the bottom in this area was not carried out due to the presence of soil sediment on it. The drawing shows that the cavities are of considerable size and concentrated in the soil thickness, mainly behind the extreme vertical walls of the structure.

The vibroacoustic diagnosis of the underground part of the Dnipro-Ingulets channel was also performed. The channel consists of two parallel tunnels, the cross-section of which is presented in Fig. 8a. The thickness of the curly reinforced concrete blocks that create the tunnel shell is 0.45 m. The internal radius of the tunnel is 2.4 m. Deterioration of conditions for the inspection and the increase in the thickness of the shell caused a significant expansion of the uncertainty range of the support technical state. After computer processing of the primary data, a picture of probable cavities behind the shell was created. Its fragment is shown in Fig. 15. The most likely position of the cavity is shown by the arrow.

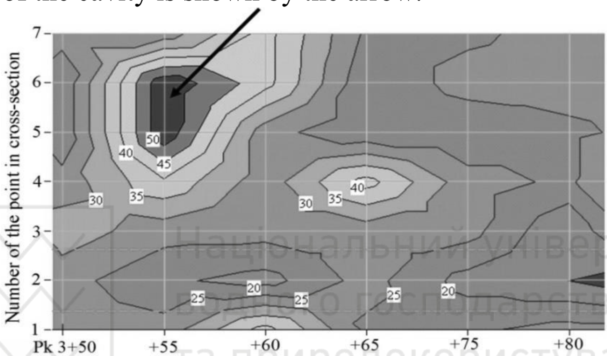

Fig. 15. A scan of fragment of tunnel № 1 of underground part of the Dnipro-Ingulets channel with vibroacoustic diagnosis results

In pressure culvert of hydroelectric station used a two-layer shell. The main layer is a monolithic reinforced concrete. The inner part of the water duct is lined with a metal sheet, the thickness of which reaches 20 mm. In case of poor contact of the metal sheet with the main concrete layer, even a strong metal shell is destroyed due to the processes of cavitation. Therefore, it is very important to identify potentially dangerous areas and take timely measures to eliminate cavities.

In the objects of this type effective is an inspection scheme with a stationary remote vibration receiver and a dense grid. Defective zones are displayed directly in the diagnostic process (Fig. 16).

A simple and effective method of strengthening the cracked contour of workings in ore mines is the applying of shotcrete. The main requirement for this type of support is a reliable adhesion of the applied layer with rocks. Vibroacoustic method is also used for operational non-destructive control of the coating quality. The thickness of the layer applied at a time does not exceed 50 mm. It can be considered as a very thin shell, and the results are displayed directly at the inspection site.

Fig. 16. The determination of the areas of poor contact of the metal to the reinforced concrete in the chamber of the working wheel of the hydraulic unit No. 12 of the hydroelectric power station in Kremenchug

The method of assessing the quality of the coating is illustrated in Fig. 17*a*. An example of detected areas of delamination is shown in Fig. 17*b*.

Fig. 17. Non-destructive control of quality application of shotcrete in the main workings of iron mine: *a* – the process of performing control, *b* – detected areas of delamination of shotcrete

Conclusions

The work shows the need to use non-destructive control methods for assessing technical state of underground structures support. A number of possible variants of control are analyzed.

The expediency of the use of the vibroacoustic method for detecting cavities in the geological environment at contact with the support and at weakening of mechanical contact of the support elements with each other is theoretically substantiated.

The choice of informative control parameters is also substantiated. The information on the development of the means for vibroacoustic control, which are designed by the Institute of Geotechnical Mechanics of the NAS of Ukraine, is provided. The methodological features of vibroacoustic control for different types of support are considered.

Examples of practical implementation of methodological provisions for different types of underground objects are given.

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