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Complex diagnostics of concrete lining technical condition

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Complex diagnostics of concrete lining technical condition

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Abstract. The main use of concrete lining is mine and hydraulic engineering construction. The options of its use in underground structures and mining operations have been considered. The advantages of this lining during construction and operation have been reflected. A long service life of underground facilities with concrete lining in Ukraine has been noted. The typical defect types have been identified. The main reasons for defect formation have been reflected. The impact of natural factors on the deterioration of the lining has been researched. The possible consequences of the flaw growth have been reported. Limited opportunities for visual inspection of the concrete surface have been noted. The main areas of non-destructive test of linings have been analyzed. The basic set of methods and control devices have been established. Special features of monitoring with various methods have been indicated. The main requirements for the registration of primary data have been defined. Typical options of office data processing have been outlined. According to the processing results, the category of the technical condition of the lining is determined. Criteria for assessing the technical condition have been presented. Specific examples of complex examination of concrete lining have been provided.

1. Introduction

For decades, concrete lining has been widely used in the construction and operation of underground structures for industrial and civil purposes. The choice of this type of lining is due to its low cost, simple construction technology and durability. The current trend of the lining development is establishment of geocomposite protective structures based on shotcrete and sprayed concrete [1-3]. At the same time, large number of objects have been maintained exclusively with concrete lining. The list of objects includes transport tunnels, underground storages and manufacturing facilities, hydraulic works, mine tunnels [4-7]. The essential criterion for their further uninterrupted functioning is timely performance of renovation works. The basis for the mentioned works performance are the results of the examination of the technical condition of the lining.

The main types of concrete lining defects are concrete strength decrease, concrete solidity decrease and occurrence of vesicles in the rock mass behind the lining. The concrete strength decrease in course of time is mainly caused by sulfidation and corrosion due to the influence of aggressive water. The concrete solidity decrease of the lining develops gradually due to the influence of thermal deformations and dynamic loads. The visual manifestation of this defect is the crack system formation on the internal face of the concrete encasement. The construction of the mounting in the form of

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separate sections is characterized with line of juncture wrecking. Frequently the wrecked lines of junctures are sources of filtration into a mine or engineering construction. Deformations of lining solidity may be also caused by relative movement of separate sections.

Hidden internal delamination of concrete can be only detected with dedicated equipment. In case of soft rocks or running measures behind the concrete encasement, cavities are formed behind due to the water motion. With large area of cavities there is perturbation of the level pressure distribution on the concrete encasement, which leads to its destruction.

The figures 1-6 depict the typical types of concrete lining defects.

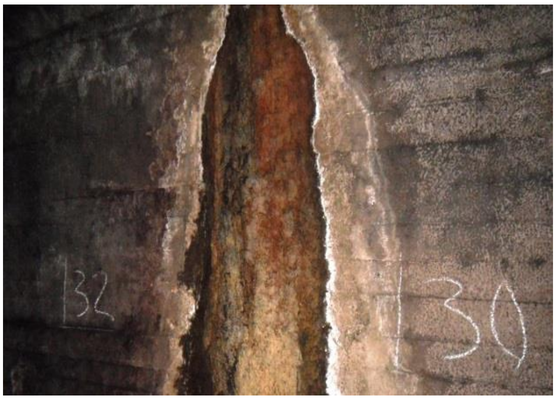

Figure 1. Water filtration through a destroyed juncture between sections of concrete lining.

Figure 2. Area of concrete corrosion in the working encasement

Figure 3. Pressure filtration of water from the cavity behind the concrete shell.

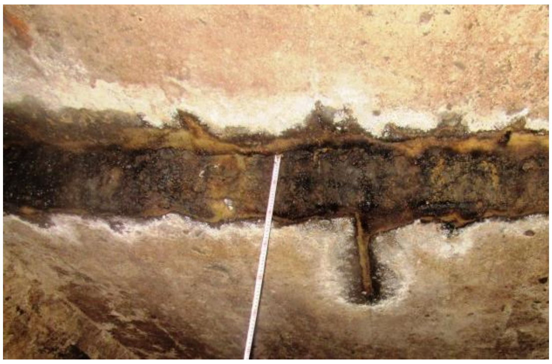

Figure 4. Vertical displacement of the concrete lining section.

Figure 5. Cracks in concrete lining.

Figure 6. Concrete surface destruction.

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Regular visual inspection is the most common inspection method of the concrete lining. It is mainly used when access to the concrete surface is complicated. An example would be surveying of mine shafts [8-10]. Continuous photographing of an object with subsequent computer processing of images is also an effective method of defining displacements [11,12]. In case of possibility to access concrete surface directly, it is advisable to use ultrasonic method or nondestructive mechanical diagnostics to determine the concrete strength [13-15]. However, a number of defects cannot be detected by visual inspection, for example, when there is uneven attachment of the concrete encasement to the surrounding rock mass [16]. The vibroacoustic method is traditionally used to detect cavities behind the shell [17,18]. Over the last decade, there has been a growing trend in the use of ground-penetrating radars for technical diagnostics of underground structures [19,20].

In Ukraine a lot of underground facilities with concrete lining have been in operation for decades. They tend to have all known types of defects. Therefore, to conduct repairs it is critical to have quantitative estimate and qualitative assessment.

The aim of this work is substantiate and to develop a multi-method estimation technique of the engineering status of lining of underground structures.

2. Methods

The main element of complex technical diagnostics is a visual examination. It is performed in several stages. The first step is to apply a dimensional grid to the surface of the lining. Usually its step is 2 m. In some cases, the step is reduced to 1 m. The best way is to mark the nodes of the grid with aerosol paint. If the concrete surface is dry and flat, you can use chalk. Figure 7 illustrates the marking procedure.

Figure 7. Marking performance on the concrete surface.

After the marking, complete surface photography is performed. The smallest frame size must exceed the grid step. Next step is image processing which results with the digital map board. The map board is the scanogram of the examined area. In the initial stage, separate photographs are joined according to the scale and with the correction of any distortions. Using the marking elements on the image, an electronic grid is applied to it. Visible defects in the picture are contoured. The following defects are distinguished: cracks, surface destruction of concrete, bulging of lining, corrosion of concrete, destruction of seams between sections, mutual displacement of sections, sources of filtration. Further work consists of characteristics clarification of the detected defects. The results are displayed on an electronic map. A typical scheme for feature selection is presented in table 1.

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Table 1. Clarification of defect characteristics.

Type of defect	Characteristics main	Characteristics additional
Crack	width filtration	crack filling
Destruction of the concrete surface	destruction depth	
Bulging of the concrete	height of the projection	
Concrete corrosion.	layer thickness	dry or wet
Destroyed seam	width destruction depth	dry or wet
Mutual displacement of the sections	displacement amplitude	dry or wet
Filter source	pressure or non-pressure	source capacity

For non-destructive control of concrete strength are used two methods: elastic rebound method and ultrasonic method. The minimum number of control points in the cross-section of a mine working or engineering structure is equal to six. Generally, there are two points on the sides and two in the vault. The default distance between controlled sections is 4 meters.

A mechanical sclerometer, such as *Schmidt Hammer 225*, is used for strength assessment with the elastic rebound method. The advantages of this method are high efficiency of control and the independence of the measurement results from the concrete composition. However, the elastic rebound method characterizes the concrete strength only at the control point. Due to the heterogeneity of the material structure, a significant variation of indicator of strength is observed.

The advantage of the ultrasonic method is averaging of concrete properties within the control base. In addition, not only the surface of concrete is monitored, but also its deeper layers. Therefore, this method is involved into the complex methodology as one of the main ones.

Novotest, a Ukrainian-made device, was put to use to control the strength of concrete with the ultrasonic method. Its special feature is the availability of ultrasonic transducers with conical concentrators. It allows to take measurements without preliminary surface preparation. The result does not depend on the surface orientation. When applying ultrasonic control, the main problem is the need to predetermine the relation between the speed of the longitudinal wave and strength of specific types of concrete.

As a rule, the strength of concrete determined with the ultrasound method is up to 20% higher than with the elastic rebound method. This is due to increase in the quality of concrete which is further away from its surface. If the results are more discrepant, the measurements are taken again in other control points. The process of strength of concrete determination with non-destructive testing methods is shown in figures 8 and 9.

Figure 8. Strength of concrete determination with the elastic rebound method.

Figure 9. Strength of concrete determination with ultrasonic method.

To detect cavities behind the concrete shell, the vibroacoustic (shock-flutter) method is used. This is the tradition of the scientific school which the authors belong to. It has been determined that in case of a cavity behind the shell, the amplitude of free oscillations increases, the frequency of the maximum spectral density decreases, and the relaxation time increases. More information on implementation options of method for various control conditions and the corresponding equipment you can find in the contributions mentioned information source [21, 22].

Special feature of this method is sharp non-linear decrease in sensitivity within increasing concrete thickness. The method is effective with concrete thickness of up to 0.5 meters. With large area of cavities, it is possible to detect them to depth of 0.8–1.0 meters. To establish the criterion for the presence of cavities based on the value of informative parameter, preliminary taring is necessary. It is performed in areas where the presence and absence of cavities is confirmed with control drilling.

The scheme of one of the options for vibroacoustic diagnostics is shown in figure 10.

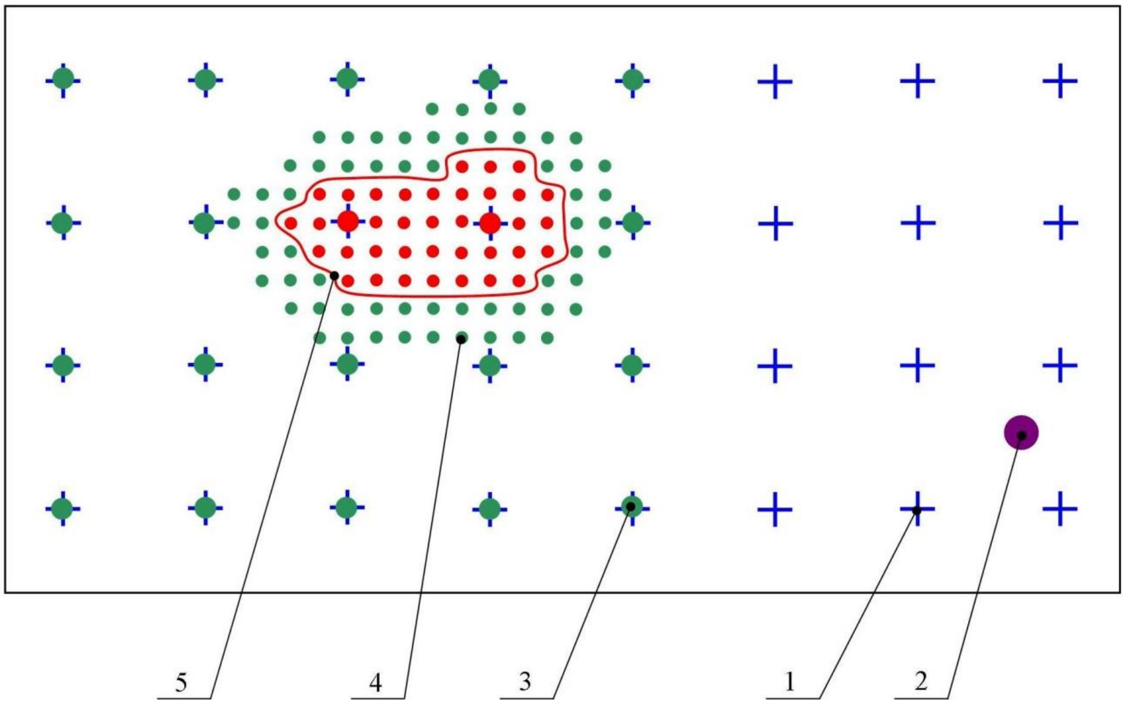

Figure 10. Scheme of cavity identification according to the results of vibroacoustic diagnostics.

Diagnostics is performed with use of a dimensional grid which has a step of 1 meter. Its nodal points are marked with position 1. For high-quality diagnostics, the maximum ratio of the useful signal to the noise level is important. This condition is met when the highly sensitive accelerometer 2 is fixed on the concrete surface with a fast-hardening solution. In most cases alabaster is used to prepare the solution. When the thickness of the concrete shell is up to 0.5 m, an ordinary hammer weighing 0.5 kg is used for impact. This ensures reliable registration of vibration during shock excitation of the concrete surface in radius of up to 10 m. With a shell thickness of about 1 m, the mass of the hammer should be about 3 kg.

When the accelerometer is in a stable position, blows are applied to the surface at points (position 3) of the first row, which coincide with nodal points of the network. If a point with an anomalous value is detected, the grid around it is thickened to 0.2 m with points (position 4) of the second row. The area with abnormal values of the parameter is contoured with a chalk as an example (position 5). After works completion on the site, the selected areas are photographed on the background of the dimensional grid. During image processing of a series of photographs, an electronic map of the cavities is prepared.

Vibroacoustic diagnostics allows to estimate the area of cavities. During the preparation process of repair works, it is necessary to know their volume. For this purpose, selective control drilling is conducted in the center of the cavities. The depth of the cavity is measured with a probe. In most cases the cavity is filled with water. After the depth measurement is completed, the hole is tamped. Figures 11 and 12 illustrate the method of practical implementation of vibroacoustic diagnostics in a concrete water pipeline of a hydroelectric power plant.

Figure 11. Excitation of vibrations in a concrete structure.

Figure 12. Distance registration of free oscillations of the structure.

Figure 13 illustrates the projection of cavities on the shell surface.

Figure 13. Selection of the contour of cavity on the results of vibroacoustic diagnostics.

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3. Results and discussion

With the use of above-described methodology, the following groups of objects were examined: underground structures with technological equipment, large-diameter water pipes, sewage collectors, vertical mine shafts, and capital horizontal workings.

On the results of complex examination there have been formulated the conclusions regarding the technical condition of the objects. The raw data for repair have been prepared. The recommendations for repair works have been elaborated.

The national regulatory framework distinguishes four categories of technical condition: 1 - normal, 2 - satisfactory, 3 - unsuitable for normal operation, and 4 - emergency.

The normal state of concrete lining refers to its full compliance with the project documentation. During examination of objects with a long service life normal state is practically not found. Satisfactory condition is typical for most of the examined objects. Detected defects allow operation in customary mode. Their presence can cause problems in the future. Defects are eliminated during planned repair works. An object that is unsuitable for normal operation can be temporarily used with certain restrictions. If necessary, operation is temporarily stopped and unscheduled repairs are conducted. The emergency state of the facility requires immediate cessation of its operation. The choice between the repair of the object and its liquidation is made by an expert. The function category of the object is also considered.

Criteria for technical condition assessment of reinforced concrete structures are well-known [23, 24]. However, concrete lining has its own specifics. As a result of regular long-term observations of its condition in various purpose underground facilities, relevant indicative criteria have been established. They are listed in table 2.

Table 2. Characteristics of defects to determine the technical condition of concrete lining.

Lining defects	Category of technical condition			
	1	2	3	4
Cracks	absence	superficial, up to 3 mm wide	deep, over 3 mm wide	along the contour of blocks with the threat of collapse
Destruction of the concrete surface	absence	local areas up to 15% of the concrete thickness	areas up to 30% of the concrete thickness without the threat of collapse	combination of local areas of destruction into extensive system
Bulging of the concrete	absence	local areas without cracks in concrete	displacement of individual sections with the destruction of the seams	deformations with the destruction of concrete and the threat of collapse
Concrete corrosion	absence	along the seams to a depth of up to 10% of the concrete thickness	areas with a corrosion depth of 10% to 25% of the concrete thickness	large areas with a corrosion depth of more than 25% of the concrete thickness
Filter source	absence	point sources of non-pressure filtration	non-pressure and pressure filtration along the seams between sections	pressure filtration with the threat of flooding
Cavities behind the shell	absence	local cavities up to 10% of the area	cavity area from 10% to 30%	over 30% of the area, with pressure water
Decreasing the strength of the concrete	up to 5% at discrete points	up to 5% in the vast majority of points	up to 30% in the vast majority of points	over 30 % in the vast majority of points

The primary data collection includes drawings, measurement results, photographs, text records. The assessment requirement for the technical state is the availability of design documentation for the object under inspection. The result of initial processing of the visual inspection data is a map of visible defects on the scan of the object surface. Occasionally it is performed in combination with the results of vibroacoustic diagnostics.

The system of symbols approved by the authors is shown in table 3.

Table 3. The system of symbols on the map of defects.

Defect	Detailing	Symbol
Crack	hairline	
	up to 3 mm wide	
	over 3 mm wide	
Destruction of the	-	
Concrete corrosion	-	
Point filter source	non-pressure	
	pressure	
Destroyed seam	dry	
	wet	

According to the results of vibroacoustic control, a cavities map is made. Numbered control drilling points are applied. Information about its results is given separately.

The contour of cavity is clearly distinguished at shell thickness of up to 0.3 m. As thickness increases, it is difficult to distinguish the contour. In such cases maps of cavities are created with three gradations: reliable absence of cavities, their reliable presence, and the transition zone.

Examples of graphical presentation of control results are given below. The authors conducted an examination of pressure water pipelines of 16 aggregates of the Dnipro hydroelectric power plant (Zaporizhia, Ukraine). Each aggregate is fitted with two water pipes with a concrete lining. The map of defects in the bottom of the water pipes from the side of upstream in the example of hydraulic aggregate No. 11 is shown in figure 14.

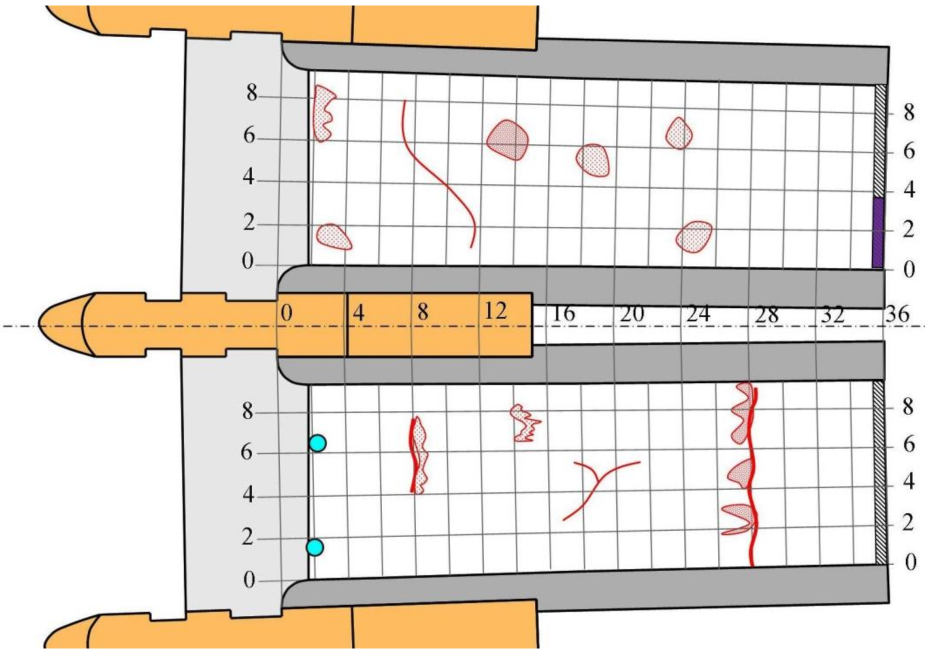

Figure 14. The results of a visual inspection of the bottoms of the penstocks.

In Dnipro, Ukraine, comprehensive diagnostics of the sewer has been performed. The sewer consists of two parallel rectangular concrete tubes (figure 15).

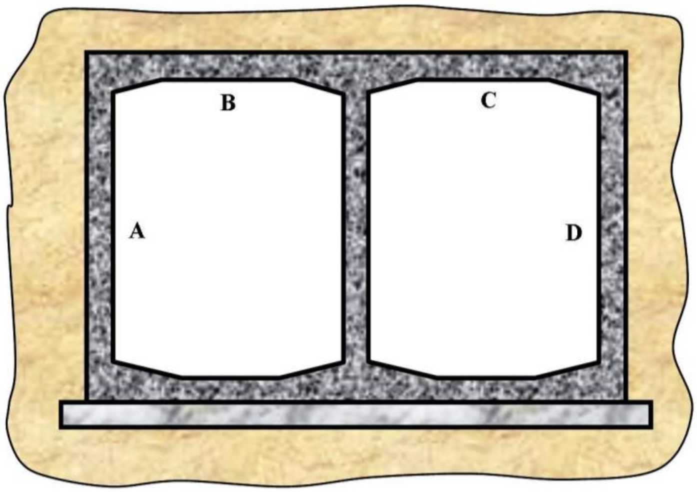

Figure 15. Cross section of a sewer with concrete tubes.

The results of vibroacoustic diagnostics of surfaces of the collector bordering the soil layer are shown in figure 16.

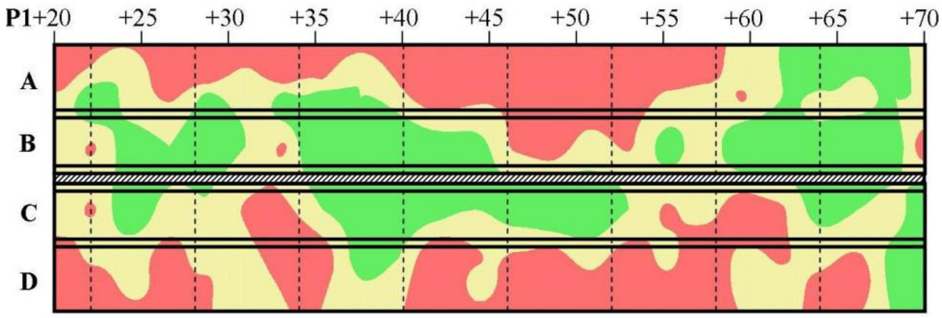

Figure 16. The results of vibroacoustic diagnostics of the collector fragment.

Zones of obvious cavities behind the shell are highlighted with red color. Green color stands for no cavities. The intermediate state is highlighted with yellow color.

The results of concrete strength measurement are illustrated in the example of cementation gallery of the Dniester HPP, Ukraine. The appearance of the gallery is presented in figure 17.

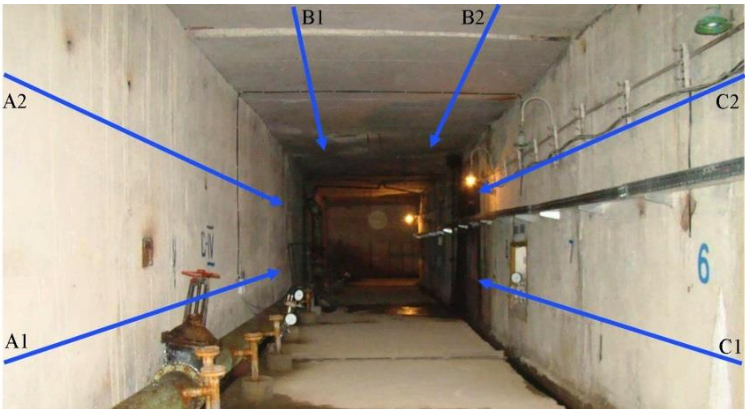

Figure 17. Control profiles in the cementation gallery in HPP.

The results of concrete strength determining with a sclerometer are shown in figure 18.

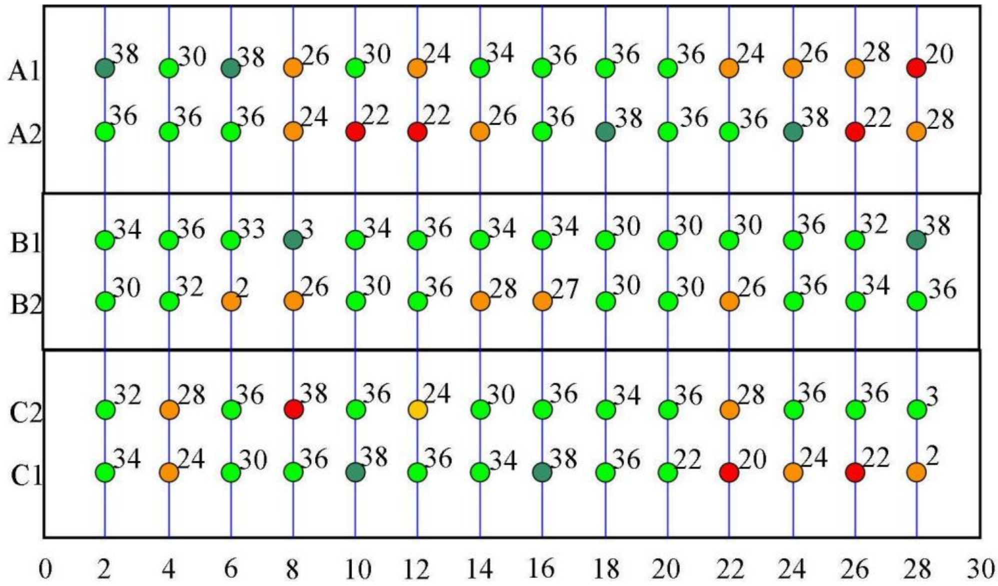

Figure 18. The results of concrete strength determining with a sclerometer.

The design value of concrete strength is 30 MPa. Symbols for strength at control points are presented in table 4.

Table 4. Symbols in figure 18.

Compliance with the project	Strength, MPa	Symbol
Below design strength	less than 24	🔴
	from 24 to 29	🟠
Relevance to the project requirements	from 30 to 36	🟢
	more than 36	● (dark green)

Other than technical condition assessment of the concrete lining, the results of the comprehensive examination are the basis for the repair works project development. The detected defects are classified according to the results of examination, and their quantitative characteristics are determined. They are summed over the entire examined surface. Typical summary information is illustrated with the example of Kyiv HPP, Ukraine viewing gallery. It is presented in table 5.

Table 5. Concrete lining defects in the Kyiv hydroelectric power plant viewing gallery.

The length of the crack, m		Destruction of the concrete		Concrete corrosion	Number of filter sources		Cavities behind the shell	
dry	wet	area, m^2	volume, m^3	area, m^2	pressure	non-pressure	area, m^2	volume, m^3
67	44	5.7	0.9	204	2	11	72	14.4

4. Conclusions

Concrete lining is widely used in construction of underground structures with a long service life. Under the influence of natural and technogenic factors, the technical condition of the lining gradually degrades. Typical defects of concrete lining have been determined, such as: surface destruction of concrete, corrosion of concrete, reduction of its strength, cracks, destruction of seams between lining sections, sources of filtration, occurrence of cavities behind the concrete shell. The technical state category of concrete lining is determined by the cumulative effect of the specified defects. There has been substantiated and developed complex method of examination of linings, which allows obtaining qualitative and quantitative characteristics of the specified defects. It includes visual inspection, concrete strength determination with non-destructive methods and vibroacoustic diagnostics. The processing of inspection results includes creation of defects map and their total calculation within the entire facility. There have been provided examples of practical use of the technique in underground structures on the territory of Ukraine.

References

[1] Galan I, Baldermann A, Kusterle W, Dietzel M and Mittermayr F 2019 Durability of shotcrete for underground support – review and update *Construction and Building Materials* **202** 465-493

[2] Sjölander A *Structural Behaviour of Shotcrete in hard Rock Tunnels* (Stockholm: BeFo Rock Engineering Research Foundation)

[3] Mehra C, Saritha P and Kumar M 2016 Shotcreting in tunnels *Int. J. of Engineering and Computer Science* **5** (8) 17667-72

[4] Clarke-Hackston N 2001 Concrete linings for tunnel built by underground construction *Tunnel* **5** 50-56

[5] Papanikolaou V K and Kappos A J 2014 Practical nonlinear analysis of unreinforced concrete tunnel linings *Tunnelling and Underground Space Technology* **40** 127-140

[6] Li D C, Xu C, Cui Z D, Chen J M, Xu X Q, Zhang T T, Zhang Z W and Song G 2022 Mechanical properties of functionally graded concrete lining for deep underground structures *Advances in Civil Engineering* **1**

[7] Pakula A, Preston R, Kennard D and Maclnnis C 2019 Stabilizing an underground void: monolithic construction using self-consolidating concrete *Proceedings of the 13th International Conference on Mine Closure* (Perth: Australian Centre for Geomechanics) 263-274

[8] Jendryś M 2019 Analysis of stress state in mine shaft lining, taking into account superficial defects *IOP Conf. Series: Earth and Environmental Science 261*(2019) 012016

[9] Tarasov V, Aptukov V and Pestrikova V 2020 Deformation and failure of concrete lining in vertical shaft at intersections with horizontal tunnels *J. of Mining Science* **56** (5) 726-731

[10] Yang Y T and Ji H G 2012 The corrosion of concrete shaft lining of mine and its related research progress *Applied Mechanics and Materials* **226-228** 976-979

[11] Inouea D, Uenoa T and Nakamura S 2018 Robotic inspection tests of tunnel lining concrete with crack light-section device on variable guide frame *35th Int. Symp. on Automation and Robotics in Construction (ISARC 2018)* 524-529

[12] Jiang Y, Zhang X and Taniguchi T 2019 Quantitative condition inspection and assessment of tunnel lining *Automation in Construction* **102** 258-269

[13] Lin S, Shams S, Choi H and Azari H 2018 Ultrasonic imaging of multi-layer concrete structures *NDT&E Int.* **98** 101–109

[14] Zhao G and Zhang D 2018 Concrete structural health monitoring with ultrasonic technique *Struct. Eng.* **34** 151-156

[15] Jedidi M 2018 Evaluation of the concrete quality using destructive and non–destructive tests *MOJCE* **4** 219-223

[16] Zhao Y, Liu C, Zhang Y, Yang J and Feng T 2019 Damaging behavior investigation of an operational tunnel structure induced by cavities around surrounding rocks *Engineering Failure Analysis* **99** 203-209

[17] Miele S, Karve P, Mahadevan S and Agarwal V 2020 *Concrete Structure Health Monitoring Using Vibro-acoustic Testing and Machine Learning* (Washington: United States Department of Energy)

[18] Blaney S and Gupta R 2018 Sounding of subsurface concrete defects using frequency response of flexural vibration *Cement and Concrete Composites* **92** 155-164

[19] Lin C, Wang X, Li Y, Zhang F and Xu Z 2020 Du Forward modeling and GPR imaging in leakage detection and grouting evaluation in tunnel lining *J. of Civil Engineering* **24** 278-294

[20] Qin H, Xie X, Vrugt J A, Zeng K and Hong G 2016 Underground structure defect detection and reconstruction using crosshole GPR and Bayesian waveform inversion *Automation in*

Construction **68** 156-169
[21] Skipochka S I, Serhiienko V M, Amelin V A and Sytnichenko O Yu 2019 Organization of geomechanical monitoring for non-metallic deposits chambers roofs *Geo-Technical Mechanics* **146** 127-139
[22] Skipochka S I, Palamarchuk T A and Sergienko V N 2018 Geomechanical monitoring for underground mining mineral deposits *Innovative development of resource-saving technologies for mining* (Sofia: St. Ivan Rilski) 147-167
[23] Kashevarova G G and Tonkov Yu L 2020 Technical diagnostics of reinforced concrete structures using intelligent systems *Magazine of Civil Engineering* **93** 13-26
[24] Todorov M 2014 Study of the conditions on reinforced concrete structures with more than 50 years of exploitation *J. of Applied Engineering* **2** 35-39