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RECOMMENDATIONS FOR THE USE OF UNDERGROUND DUAL-USE STRUCTURES IN UKRAINIAN REALITIES

Skipochka S., Serhiienko V., Musiienko S., Prokhorets L.

M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine

Abstract. The purpose of the work is to perform an analysis of the world experience of multi-purpose use of underground structures and to provide recommendations on monitoring the technical condition and technology of repair and restoration works of underground and buried dual-use objects for their operation in the conditions of Ukrainian realities. The main areas of use of underground structures for additional purposes are considered. In particular, for the equipment of warehouses, isothermal factories, specialized research laboratories, medical institutions with special conditions, tourist facilities. Under martial law, underground facilities are also used to shelter civilians, organize the production of defense products, hold mass cultural events, and create first aid stations for victims. There are two main categories of dual-use underground structures. The first one includes mining workings in the abandoned areas of mines. The main requirements for the workings are a large cross-section, satisfactory natural stability, the absence of harmful gases in the mine atmosphere, and the absence of the threat of flooding. It is desirable to be able to drive vehicles from the earth's surface directly to the required object. These requirements are implemented mainly in mines for the extraction of non-metallic building materials. The second category includes underground hydraulic structures, transport tunnels, basements of industrial enterprises and residential buildings. The main requirements for the performance of additional functions are the provision of full operation of the building for its primary purpose and the creation of safe conditions for people without special knowledge and skills. To assess the possibility of expanding the operational capabilities of underground structures, a methodology for their survey has been developed. The methodology involves a visual assessment of the state of rock exposures and fasteners, determination of the strength of rocks and concrete mainly using non-destructive control methods, detection of cavities behind the shell of an underground structure using the vibroacoustic method. In some cases, control drilling is performed. The presence of people without personal protective equipment in the dual-use underground structure places higher requirements on the stability of structures. To increase the stability of the mine workings, additional fixing of the roof of the workings with anchors, application of shotcrete on rock outcrops and the surface of the destroyed support, creation of canopies in areas where people are concentrated are provided. Increasing the stability of underground structures, which are not related to the extraction of minerals, is achieved by strengthening and installing additional load-bearing structures. To improve the waterproofing of the underground structure, it is recommended to fill the cavities behind the shell, eliminate filtering fractures, repair the seams between the sections of support, and apply a penetrating coating.

Keywords: underground structure, dual-use, technical requirements, survey, increasing stability, improving waterproofing.

1. Introduction

In wartime, our country's priorities are aimed at increasing defense capability and protecting the population. Various underground structures provide natural secrecy and protection from direct attacks, bombings and missile strikes. Therefore their use for the main and additional purpose acquires strategic importance. The main areas of underground structures application that are relevant for Ukraine are the location of production facilities, mining, equipment for military and infrastructure facilities, warehouses, shelters for the protection of the population, etc. It is possible to simultaneously use underground space to perform several functions. The preservation and re-equipment of existing underground structures of the mining complex, transport tunnels, metro and other infrastructure is the main component of achieving this goal. It should also be noted that in large cities, the construction of underground infrastructure facilities solves the problems of efficient use of territory. In addition, projects such as underground parking lots, transport tunnels and shelter facilities contribute to the development of seismically safe and ecological construction, protect against ex-

treme climatic conditions, preserve the natural landscape, solve the problem of transport.

It should be noted that, firstly, in Ukraine, unfortunately, there is not enough experience in mass construction and the use of underground structures for dual-use. Secondly, such objects are subject to increased requirements regarding the safety of their operation, especially the characteristics of dynamic and long-term stability. Thirdly, as is known, the effectiveness of measures aimed at improving the operational reliability of underground structures depends significantly on the timely identification of factors affecting their stability and the implementation of repair and restoration works.

Therefore, the purpose of this work is to analyze the world experience in the operation of dual-use underground structures and develop recommendations for the organization of objects monitoring, as well as technological solutions for the implementation of urgent repair and restoration work to improve the technical condition of the structure.

2. Methods

The paper analyzes foreign and domestic information sources. The results of own research, carried out according to the methodology for assessing the technical condition of structures developed and implemented in Ukraine at underground facilities of various purposes are summarize. According to the methodology, the initial stage of the survey is a visual inspection. In the case of a mine working, it primarily provides for a preliminary assessment of the roof condition [1]. In the areas without support, cracks, rock fragments, zones of stratification, moisture and filtration, as well as signs of geological disturbances are recorded. Photographs are taken and the geometric dimensions and position of the detected defects are determined. If there is a metal support, the degree of its corrosion is visually assessed and signs of deformation are recorded. Next, rock blocks are evaluated on vertical outcrops. During a visual inspection of reinforced concrete support, record areas of concrete corrosion, exposed reinforcement, fractures, areas of moisture and obvious filtration. It is mandatory to determine the position and geometric dimensions of the detected defects. To detect delamination in the roof the vibroacoustic method is use [2]. The maximum depth of detection of delaminations by this method is about 1 m. Refinement of the structural structure of the roof is carried out by control drilling with subsequent endoscopy of the borehole [3]. An approximate assessment concrete of support strength and rock mass is carried out using non-destructive testing methods [4], in particular, ultrasonic and elastic rebound methods. For a more accurate assessment, samples of the material are taken and tested in the laboratory.

A similar determination of the support material strength is carried out in underground structures not associated with mineral extraction. This category of buildings is often located in the soil layer, where the formation of cavities behind the shell of the structure is possible. Their preliminary detection is carried out using vibroacoustic method. The cavity volume is specified by conducting control drilling.

3. Results and discussion

Analysis of the world experience of dual use of underground structures.

Based on the analysis results, the following classification of underground dual-use facilities was developed (table 1).

Table 1 – The classification of dual-use underground structures

Main purpose	Additional purpose	Using
Underground workings of mining enterprises	Special productions	Permanent
	Health complexes	Permanent
	Warehouses	Permanent and temporary
	Unique scientific objects	Permanent
	Air alarm shelter	For the period of special condition
Underground transport communications	Placement of retail outlets	Permanent and temporary
	Equipment of assistance points	For the special condition period
	Air alarm shelter	For the special condition period
Hydrotechnical structures not filled with water	Air alarm shelter	For the special condition period
Basements of industrial enterprises and residential buildings	Creation of small industries and retail facilities	For the special condition period
	Air alarm shelter	For the special condition period

It is established that in the world practice significant experience has been accumulated in the use of mine workings for the placement of objects not related to the extraction of minerals [5–13]. The most suitable for this purpose are mines for the extraction of building materials. Their advantages are a small depth. Low rock pressure ensures long-term stability of large section workings after mineral raw material extraction. Particularly effective was the arrangement in the underground workings of wineries. The main motive for their placement underground is a stable temperature and humidity. At present, there are several such enterprises in Italy, France, Moldova and other countries, as well as in Ukraine, in particular the Donbas (Fig. 1).

There is experience in creating defense enterprises in spent mines [14]. The importance of this was realized during the Second world war. For example, in Germany, Projekt Riese commissioned 143 underground enterprises that produced military products. Among the most significant were plants for the production of V-2 missiles, He-162 and ME 262 fighters. Due to the bombing, underground defense production was established in the UK. So Plessey defense electronics moved production to unfinished subway tunnels. The plant had about 2,000 employees. The Bristol Airplane Company established the production of aircraft engines in the Drakelow tunnels. The Longbridge underground plant in Birmingham also produced similar products. It employed up to 10,000 people. Similar high-tech enterprises were created in other European countries. An example is the underground aircraft factory of the Swedish company SAAB. It work began in 1944 and continued in the post-war period [15] (Fig. 2).

Figure 1 - Champagne wine factory in gypsum mine workings (Bakhmut)

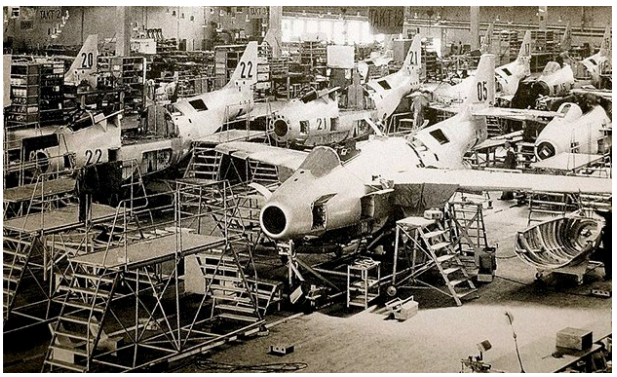

Figure 2 - Underground aircraft factory of the Swedish company SAAB

During the Cold War, underground mining was actively equipped with storage facilities and shelters for the population. This case was most carefully approached in the United States, where a targeted program for the mass creation of anti-radiation shelters was adopted at the state level. In Nevada alone, 67 such structures were prepared. After the end of the Cold War, most of the buildings were converted into warehouses (Fig. 3).

The arms race stimulated the creation of various levels of protection shelters in underground workings and in the USSR. A developed transport infrastructure was envisaged to deliver people to places of shelter. The shelters and additional structures that necessary for their functioning were constantly maintained in a state of readiness. After the end of the Cold War and the collapse of the USSR, a significant part of the structures was dismantled or failed.

Real experience in creating protective shelters in mine workings has already been accumulated in Ukraine. At this stage of warfare in Ukraine, the aggressor does not use means of mass destruction. This makes it possible to create shelters for which the requirements are significantly reduced compared to anti-radiation shelters. For shelter equipment, mine workings for the extraction of natural building materials such as limestone, gypsum, marble, granite, etc, are best suited. It is also possible to use caves of natural origin after a thorough assessment of their stability [16]. An example of creating the shelter in a mine workings is illustrated in Fig. 4.

Foreign experience indicates the possibility of shelter equipment for the population in transport tunnels too. In this regard, the leading position among European countries is Switzerland. Here a large number of road tunnels in the highlands adapted to the tasks of civil defense. One of the most famous is the Sonnenberg road tunnel [17]. From the very beginning it was considered as a dual-use building. If necessary, the tunnel could accommodate up to 20 thousand people. The project provided for a hospital, administrative offices and even a police detention center for violators. Care of these facilities continued until 2006. By that time, more than five thousand structures have already been prepared to replace it for sheltering people, which meets the needs of the population by 114%.

Figure 3 - Underground storage in limestone mine workings (USA)

Figure 4 - Shelter in the working of Sokiryansky deposit of sawn limestone (Ukraine)

In Ukraine, from the first days of the war with the Russian Federation, underground objects of urban infrastructure were adapted for the short-term protection of a large number of the population [18]. The most effective is the use of metro stations. So the Kyiv metro at its 46 stations is able to protect up to 30,000 people. Regular shelling of Kharkiv made it necessary to create conditions at each of its 30 stations for a longer stay of people. There are sanitary units, the issuance of drinking water, charging gadgets, special services for small children. Metro in Dnipro has 6 stations. But each of them during an air alarm can protect up to 1000 people. At night, subway cars are open at stations for a more comfortable stay of people.

The world has accumulated considerable experience in the use of mine workings in salt mines as medical and sanatorium facilities [19–21]. Sanatoriums, clinics and hospitals operate successfully in Poland, Romania, Pakistan, Turkey and other countries. There is also experience in creating similar institutions in Ukraine. Before the flooding of mine No. 8 in Solotvyno, a unique underground allergy-treatment department functioned in it. In December 2021, an underground health and tourist complex was opened in Soledar at mine No. 1, horizon 288 m.

Underground workings at great depth are used to accommodate research laboratories sensitive to technogenic influences and natural phenomena characteristic of the earth's surface [22–24]. Among the most famous are Sanford, Soudan and KURF laboratories (USA), SNOLAB (Canada), Large Hadron Collider (Switzerland), Gran Sasso (Italy), CJPL and JUNO (China), Super-Kasso amiokande (Japan) and others.

As an object of effective protection of personnel during an air alarm, a network of underground hydrotechnical structures, which is available at a number of industrial enterprises, can be used. Some of them is used for supplying or draining water, and in other structures equipment is installed or engineering networks are laid. Such objects have satisfactory waterproofing and reliable supports.

Recommendations on organization of technical condition of structures monitoring.

The authors have developed a methodology for a comprehensive survey of underground structures to justify the possibility of their use for an additional purpose [25]. Typical requirements for the structure are to increase their stability and improve wa-

terproofing. Information on the recommended basic survey methods is given in table 2. Examples of the use of survey methods are illustrated in Fig. 5–8.

Table 2 – Methods of underground structures survey to expand the scope of their use

The direction of survey	The element of construction	Survey methods
Detection of elements with reduced stability	The roof of mine workings	The visual inspection, vibroacoustic diagnostics, control drilling, borehole endoscopy, the rock sampling, laboratory determination of strength parameters
	The support pillar	The visual inspection, control drilling, borehole endoscopy, the rock sampling, laboratory determination of strength parameters
	The anchoring with mesh	The visual inspection, selective determination of anchors fastening strength
	The frame support	The visual inspection, determination the shape and the actual cross-sectional area
	The sprayconcrete support	The visual inspection, determination of delamination areas by the vibroacoustic method
	Concrete and reinforced concrete supports	The visual inspection, determination of concrete strength by non-destructive methods
Identification of increased water filtration causes into the underground structure	The contour of unsupported underground workings	The visual inspection, control drilling
	A closed shell of an underground structure	The visual inspection, determination of geometric dimensions of fractures with filtration, determination of cavities behind the shell by the vibroacoustic method, control drilling
	The seam between adjacent shell sections	The visual inspection, determination of the filtration section geometric dimensions
	The soil mass around the non depth bedding structure	Electrical exploration on the earth's surface

Figure 5 – Visual survey with determination the size and position detected defects

Figure 6 – Determination of the concrete shell of the underground structure strength with a sclerometer

Figure 7 – Column survey using the ultrasonic method

Figure 8 – Determination of cavities behind the shell by the vibroacoustic method

Information about some established features of non-destructive testing is given in the table 3 and 4.

Table 3 – Approximate assessment of concrete quality by longitudinal ultrasonic wave velocity (V_p) and additional visual features

The velocity V_p, m/s	Additional visual features	Concrete condition
Above 4000	Absence of fractures and inrush	Normal
From 3000 to 4000	Absence of fractures and inrush	Satisfactory
Less 3000	Surface fractures and single inrush	Limited operable
	Block structure of concrete	Emergency

Table 4 – Evaluation of vibroacoustic control results

Typical defects of the protective constructions	The nature of the informative parameter change	The need for additional survey
Hidden delamination in the rock mass or monolithic concrete support	Decrease in the maximum frequency of the free oscillations spectral density	Control drilling to determine the delamination thickness
	Increase of the amplitude oscillations	
	Increase of the duration oscillations	
Presence of a cavity behind the shell	Sharp increase of the amplitude oscillations within the contour on the shell surface	Control drilling to determine the depth of the cavity
Increased load on the support section	Reduction of the free oscillations amplitude	Visual survey to detect deformations of the section
Rock chips in the rock mass or monolithic concrete fastening	Presence of several maxima in the free oscillation spectrum	Thorough visual survey
	Significant change of the oscillations amplitude in a small area	
Hidden defects in monolithic concrete structures with the possibility of two-way access	Decrease of the oscillations amplitude on certain profiles	Control drilling
	Decrease in the frequency of the spectral density maximum or the presence of several maxima	

Conclusions about the possibility of expanding the operational capabilities of the underground structure are made based on the results of the survey. The main requirements for all structures are: the absence of roof collapse threats (in the case of mining workings) and water penetration, the absence of harmful gases entering the structure, minimizing the risk of fire. Additional criteria are listed in table 5.

Table 5 – Specific criteria for assessing the possibility of using the underground structure for the additional purpose

Main purpose	Additional purpose	Additional requirements
Mine working	Organization of isothermal production	Stability of temperature and humidity
	Creation of underground storage	Possibility of vehicles entry from the earth's surface, limitation of humidity level and temperature range
	Placement of a special purpose facility	Possibility of a significant increase in the safety margin of the support at economically reasonable costs
	Placement of shelter	Possibility of additional support of the roof in the zone of people's stay, providing the possibility of their rapid movement
	Organization of a medical facility	Ensuring the required temperature and humidity range, increased requirements for ventilation mode, reinforced roof support
Transport tunnel	Placement of shelter	Proximity to the exit to the earth's surface
Underground hydraulic structure	Placement of shelter	Placement above the water level of the adjacent reservoir, availability of an emergency exit
Basement of a house or industrial enterprise	Placement of shelter, organization of small-scale production, creation of retail outlets and first aid stations	Possibility of strengthening columns with a large basement area, availability of an emergency exit

Recommendations for repair and restoration works.

In the document [25], the authors also developed a set of standard technical solutions to improve the technical condition of the underground structure in accordance with its additional purpose. In many cases, the operation of the structure involves the constant presence of people without special skills of behavior in underground conditions. Therefore, additional security measures should be implemented and conditions for comfortable work of the staff should be created. Information on the main types of repair and restoration work when preparing the structure for additional functions is given in Table 6.

An illustration of some types of repair work in underground structures performed according to our recommendations [26, 27] is given in Fig. 9–12.

Table 6 – Main types of repair and restoration works to improve technical condition of dual-use structures

Direction of improvement	Types of repair works
Increasing the level of security	Installation of anchors with mesh on unsupported sections of the roof in mine workings, strengthening of rocks in the near-contour zone, application of spray concrete on rock outcrops in the sides of the workings, reinforcement of load-bearing structures and installation of additional support, creation of canopies in crowded places
Increasing the comfort for the work of the staff	Tamponage of cavities behind the shell to reduce water leaks, elimination of filtration fractures, application of shotcrete to areas of concrete corrosion, application of penetrating materials to the concrete shell, repair of damaged seams between sections of reinforced concrete support
Aesthetic improvement	Applying a decorative coating to the surface of the protective shell, painting metal structures

Figure 9 – Reinforcement of the weakened section of the structure shell with spray concrete

Figure 10 – Sand blasting surface of underground structure shell

Figure 11 – Strengthening the floor of underground structures

Figure 12 – Tamponage of cavities behind the shell of an underground structure

4. Conclusions

Analysis of foreign and domestic experience showed high efficiency of using underground structures for dual uses. The categories of structures most suitable for performing additional functions are allocated. These are mine workings of shallow mines, transport tunnels, underground hydraulic structures, basements of industrial enterprises and the residential sector.

It has been established that the most appropriate forms of using underground structures for additional purposes are: the organization of productions that require stable temperature and humidity parameters, and productions for the needs of defense, the creation of warehouses, shelters for the population during martial law, and underground medical complexes.

The need for a special technical survey of underground structures to determine their suitability for dual use operation is shown. The survey methodology which is focused on the predominant use of methods and means of non-destructive control is proposed. The strength of rocks and concrete, the presence of stratification in the roof of the workings and the presence of cavities behind the shell of the underground structure are determined in the control process. Control drilling is used to clarify the results.

Decisions regarding engineering measures to improve the technical condition of the underground structure are made based on the results of the survey. The following main direction of repair and restoration work have been identified: additional fixing with anchors of the mine workings roof, application of sprayed concrete on the rock mass surface and damaged reinforced concrete support, cementation of the concrete surface. To improve the waterproofing of the underground structure shell the elimination of filtering fractures and seams and the application of a penetrating coating on the concrete surface are provided.

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About authors

Skipochka Serhii, Doctor of Technical Sciences (D.Sc.), Professor, Leading Researcher in Rock Mechanics Department, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, skipochka@ukr.net, ***ORCID 0000-0002-3996-5972.***

Serhiienko Viktor, Candidate of Technical Sciences (Ph.D.), Senior Researcher, Senior Researcher in Rock Mechanics Department, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, viictorms@ukr.net, ***ORCID 0000-0002-7374-0654.***

Musienko Serhii, Candidate of Technical Sciences (Ph.D.), Senior Researcher, Senior Researcher in Rock Mechanics Department, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, mspdop@i.ua, ***ORCID 0000-0003-2594-8554.***

Prokhorets Liliia, Candidate of Technical Sciences (Ph.D.), Senior Researcher in Rock Mechanics Department, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, prohoreclv@gmail.com, ***ORCID 0000-0002-3968-9875.***

РЕКОМЕНДАЦІЇ З ВИКОРИСТАННЯ ПІДЗЕМНИХ СПОРУД ПОДВІЙНОГО ПРИЗНАЧЕННЯ В УКРАЇНСЬКИХ РЕАЛІЯХ

Скіпочка С., Сергієнко В., Мусієнко С., Прохорець Л.

Анотація. Мета даної роботи – виконати аналіз світового досвіду багатоцільового використання підземних споруд і надати рекомендації щодо моніторингу технічного стану та технології ремонтно-відновлювальних робіт підземних і заглиблених об'єктів подвійного призначення для їх експлуатації в умовах українських реалій. Розглянуто основні сфери використання підземних споруд за додатковим призначенням. Зокрема, для обладнання

складських приміщень, ізотермічних виробництв, спеціалізованих науково-дослідних лабораторій, медичних закладів з особливими умовами, туристичних об'єктів. В умовах воєнного стану підземні споруди використовуються також для укриття цивільного населення, організації виробництва продукції оборонного призначення, проведення масових культурних заходів, створення пунктів для надання першої допомоги потерпілим. Виділено дві основні категорії підземних споруд подвійного призначення. До першої належать гірничі виробки на відпрацьованих ділянках шахт. Основними вимогами до виробок є великий поперечний переріз, задовільна природна стійкість, відсутність шкідливих газів в шахтній атмосфері, відсутність загрози затоплення. Бажаною є можливість заїзду транспортних засобів з земної поверхні безпосередньо до необхідного об'єкта. Вказані вимоги реалізуються переважно в шахтах з видобутку нерудної будівельної сировини. До другої категорії належать підземні гідротехнічні споруди, транспортні тунелі, підвальні приміщення промислових підприємств та житлових будинків. Головними вимогами при виконанні підземною спорудою додаткових функцій є забезпечення її повноцінної експлуатації за основним призначенням та створення безпечних умов для людей без спеціальних знань та навиків. Для визначення можливості розширення експлуатаційних можливостей підземних споруд розроблено методику їх обстеження. Вона передбачає візуальну оцінку стану породних оголень та кріплення, визначення міцності гірських порід і бетону переважно з використанням неруйнівних методів контролю, виявлення порожнин за оболонкою підземної споруди з використанням віброакустичного методу. В окремих випадках виконують контрольне буріння. Присутність в підземній споруді подвійного призначення людей без засобів індивідуального захисту ставить більш високі вимоги до стійкості споруд. Для посилення стійкості гірничих виробок передбачено додаткове закріплення покрівлі виробок анкерами, нанесення торкретбетону на породні оголення і поверхню зруйнованого кріплення, створення навісів в місцях скупчення людей. Підвищення стійкості підземних споруд, що не пов'язані з видобутком корисних копалин, досягається шляхом підсилення та встановлення додаткових несучих конструкцій. Для поліпшення гідроізоляції підземної споруди рекомендовано тампонаж порожнин за оболонкою, ліквідацію фільтруючих тріщин, ремонт швів між секціями кріплення та нанесення пенетруючого покриття.

Ключові слова: підземна споруда, подвійне призначення, технічні вимоги, обстеження, підвищення стійкості, покращення гідроізоляції