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GEOLOGICAL ASPECTS OF THE CONSTRUCTION OF UNDERGROUND FACILITIES IN UKRAINE

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Abstract. Underground construction is becoming increasingly vital in the context of growing urbanization, a shortage of undeveloped areas, and the need to preserve the natural environment. Building residential, public, and industrial structures underground necessitates a thorough analysis of geological, geophysical, and hydrogeological conditions that affect their safety, durability, and economic feasibility. This article examines the primary geological, geophysical, and hydrogeological factors influencing the underground construction of residential, public, and industrial facilities. It assesses their impact on site selection, structural features, and the safety of these facilities. The article highlights methods for exploring underground spaces and offers recommendations for minimizing risks. Both favourable and adverse geological factors for conducting underground construction are identified and analysed, with brief characteristics provided. Considering these factors, the general principles of geological zoning in territories, particularly within the Ukrainian Crystalline Shield (UCS), are established. The most suitable areas for underground construction of public, industrial, and military facilities are those classified as simple structure (the Ist category of complexity) based on engineering and geological conditions. Specifically, these are territories with a low level of seismicity; areas featuring monolithic strong hard rocks (granites and gneisses); regions with a stable geological environment, minimal impact from fault zones and unfractured rocks, or rocks with low fracturing; and areas with stable hydrogeological conditions and low levels of non-aggressive groundwater. The article analyses the underground construction experience in countries (Sweden, Norway, Finland) within the Baltic Crystalline Shield, demonstrating the general similarities in structure and geological conditions between the Baltic Shield and the UCS. It is underscored that in Ukraine, it is most prudent to seek optimal sites for locating underground facilities within the Ukrainian Crystalline Shield. The final decision regarding the facility's location should be made with consideration of its specific designed purpose and requirements, adhering to building rules and regulations.

Keywords: underground construction, geological factors, hydrogeology, engineering geology, geophysical research, Ukrainian Shield.

1. Introduction

At this stage in societal development, underground construction is becoming increasingly relevant due to population growth, urbanization, environmental challenges, and the need for safety. Utilizing underground space allows optimization of urban infrastructure, enhances the stability of structures, and lowers environmental impact. This issue encompasses key elements of the importance of underground construction, such as urbanization and spatial constraints, environmental and energy challenges, transport infrastructure and logistics, security and defence capabilities, the construction of industrial and scientific facilities, and innovative technologies. Let us examine these aspects in greater detail.

Urbanization and spatial restrictions. The development of megacities, population growth, and shortage of land resources force us to look for alternative solutions for the placement of transport, residential, and commercial infrastructure. The use of underground space allows you to reduce the density of construction on the surface, preserving recreational areas and historical heritage. In conditions of high density of construction, underground construction becomes an effective solution for the placement of public, transport, and residential facilities. Underground spaces are used to accommodate subways and tunnels, which helps improve transport logistics, parking lots, reduce street congestion, accommodate shopping centres and underground passages, and increase accessibility to facilities for the population.

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Environmental and energy issues. Underground structures have several environmental advantages, namely, they reduce the impact of construction on the environment, preserving the natural landscape, use the natural thermal insulation of the soil, which increases energy efficiency, promote the development of geothermal stations, which provides alternative energy sources and the use of underground storage for renewable energy (accumulation tanks).

Transport infrastructure and logistics. The development of underground transport infrastructure is important for unloading surface routes. Overpasses and freight logistics hubs ensure efficient and safe transport movement. Such solutions reduce traffic congestion, increase the speed of goods and passenger transportation, and optimize urban space by placing infrastructure facilities underground.

Security and defence capability. In modern conditions, underground construction plays an important role in ensuring the protection of the population and critical infrastructure. In particular, underground shelters and bomb shelters are necessary to protect against military threats, terrorist attacks, and natural disasters. In addition, seismically resistant underground structures can reduce the risk of destruction during earthquakes. Underground water and fuel storage tanks provide independence in emergencies. In addition, given the war in Ukraine and the threat of modern military conflicts, underground construction of military facilities remains one of the most effective ways to protect critical infrastructure, increase the combat capability of troops, and maintain strategic balance.

Construction of industrial and scientific facilities. Underground space is actively used in science and industry. In particular, underground laboratories such as CERN (Conseil Européen pour la Recherche Nucléaire) in Switzerland allow research to be conducted under conditions of minimal external influence. Underground warehouses, tanks, and industrial facilities, such as hazardous materials storage facilities, are effectively used to store hazardous materials and resources, located underground to reduce risks to the public and the environment.

Innovative technologies for underground construction. Technological development contributes to the expansion of the possibilities of underground construction. Modern methods include, in particular, the use of composite materials that increase the durability of structures, new technological monitoring and diagnostic systems for monitoring the technical condition of structures, automation, and robotic construction technologies. The latest technologies, in particular, 3D printing of concrete structures, automated tunnelling, and the use of artificial intelligence for the design of reinforced structures, open up new opportunities for effective underground construction.

Thus, underground construction is a strategic direction for the sustainable development of cities and industry, which allows solving the current problems of urbanization, transport, ecology, and safety. Thanks to modern technologies, it has become more accessible, more efficient, and environmentally friendly. Further development of this industry will contribute to the optimization of space, energy efficiency, and an increase in the level of protection of infrastructure facilities. Beyond that, especially given the ongoing aggression of the Russian Federation against Ukraine, underground and buried structures play a critically important role in ensuring the security of the population, strategic facilities, and infrastructure during military operations.

The purpose of the work is to analyse and evaluate the impact of geological, geophysical, and hydrogeological factors determining for underground construction, residential, public, and industrial facilities, to define the main principles of zoning territories according to their suitability for underground construction.

Achieving the set goal involves solving many tasks, namely: analysing current regulatory documents and engineering and geological prerequisites for underground construction, determining the main principles of underground construction of residential, public and industrial facilities, identifying favourable and negative factors of underground construction, determining criteria for zoning territories for selecting sites for underground construction.

2. Methods

Methods – the analytical review of the general state of the problem, an analysis of the existing regulatory framework for engineering and geological prospecting works and underground construction, an analysis and generalization of world experience in conducting underground construction, an analysis of the geological structure of the Ukrainian territory, in particular traditional methods of analysing available geological information – geological maps, geological sections, etc., zoning of the territory based on a survey of favourable and negative factors of underground construction for the selecting the promising sites.

3. Theoretical part

In Ukraine, underground construction is regulated by many regulatory documents – DBN and DSTU, the main ones being [1–9]. DBN V.1.1-45:2017 "Buildings and structures in complex engineering and geological conditions. General provisions" [5] establishes general requirements for the design of buildings and structures in complex engineering and geological conditions. DBN V.1.2-14-2018 "General principles for ensuring the reliability and structural safety of buildings, structures, building structures and foundations" [2] has provisions on determining the complexity categories of construction objects and their relationship with engineering and geological conditions. The complexity of engineering and geological conditions is separately regulated by standards [1, 4, 7–9]. DBN A.2.1-1-2014 [1] and DSTU B V.2.1-28:2010[7] "Engineering Surveys for Construction" establish the main provisions and requirements for conducting engineering surveys for construction on the territory of Ukraine, in particular, they define the categories of complexity of engineering and geological conditions. DBN V.1.1-12:2009 "Construction in seismic areas of Ukraine" [4] is used for facilities located in seismically hazardous regions. The document specifies how seismicity is taken into account when determining the complexity of conditions. DSTU-N B V.1.1-27:2010 "Guidelines for the implementation of engineering and geological surveys" [8] contains recommendations for assessing the complexity of engineering and geological conditions, including by categories (simple, medium complexity, complex). The categories are determined by the number of engineering and geological elements, depth of occurrence, presence of hazardous geological processes, soil conditions, etc. DSTU 9275.1:2024 [9] defines the procedure for organizing, performing, and registering the results of engineering and geological surveys, which are necessary for the design and construction of facilities.

At the international level, the regulation of the complexity of engineering and geological conditions may differ depending on the country. Many states develop their own standards and regulatory documents that consider local geological features and construction practices. In the countries of the European Union, the Eurocode 7 "Geotechnical design" series standards [10] are often used, which set general principles of geotechnical design and soil classification. It is worth noting that although international standards provide general recommendations, each country adapts them following its specific conditions and requirements. In Ukraine, this standard is adopted as [11].

According to [7, 8], engineering and geological conditions are divided into three categories of complexity:

1. Simple (Category I): They are characterized by homogeneous soils and stable hydrogeological conditions.
2. Medium complexity (Category II): They are characterized by diverse soils and possible changes in hydrogeological conditions.
3. Complex (Category III): They include the presence of specific soils, high groundwater levels, seismic activity, and other factors that complicate construction.

The classification of the complexity categories of sites according to engineering and geological conditions is based on the evaluation of various geological, hydrogeological, geomorphological, and other factors.

Category I (simple) is characterized by favourable engineering and geological conditions: a homogeneous and stable soil massif, the absence of significant tectonic disturbances and karst formations, a stable groundwater level with a minor impact on building structures, the absence or minimal manifestations of exogenous geological processes (landslides, erosion, flooding, etc.).

Category II (medium complexity) has certain restrictions that may complicate construction, in particular, the presence of heterogeneous or weak soils (clayey, sandy-loam, sandy soils with variable characteristics), the presence of water-saturated soils with an elevated groundwater level, manifestations of local geological processes (suffusion, karst, flooding, minor landslides), the possibility of seismic impacts of medium intensity (up to 7 points on the EMS-98 scale [12] or similar).

Category III (complex) is characterized by complex engineering and geological conditions that significantly complicate construction, namely: complex geological structure (mixed, heterogeneous soils, prone to subsidence, swelling or landslides), high groundwater level or aggressive environment affecting the foundation and building materials, intensive geological processes (active karst, landslides, flooding, erosion, suffusion, subsidence of soils), high seismic hazard (from 7 points and more [12]), the presence of faults or zones of active tectonics.

Among additional factors affecting the complexity categories for underground construction in terms of engineering and geological conditions it is necessary to note hydrogeological conditions (groundwater, its level and aggressiveness), geomorphology – the terrain relief (steep slopes, erosion forms, tectonically active zones), climatic conditions (frost heaving of soils, changes in humidity, seasonal fluctuations in water level) and anthropogenic impact (urbanization, man-caused loads, real estate development, recultivation).

This classification helps to determine measures for engineering preparation of the territory, the choice of the type of foundations, and the prediction of possible complications during construction. Engineering and geological surveys to substantiate underground construction should be carried out with a completeness sufficient to assess the construction conditions and develop forecasts of the interaction of the geological environment with underground structures [13–16].

4. Results and discussion

The main principles of underground construction of residential, public, and industrial facilities are based on engineering, geological, economic, and environmental aspects. The main principles of such construction should include:

1. Geotechnical and geological aspects – research of soils and hydrogeological conditions before construction, concerning seismic activity and possible geodynamic processes, use of soil strengthening methods for stability of structures.
2. Structural and engineering solutions – the use of durable materials resistant to moisture, chemical influences, and mechanical loads, design of ventilation, lighting, and drainage systems for manufacturability and safety.
3. Functional features depending on the purpose of the facility – residential underground premises require the presence of life support and evacuation systems, public underground structures (shopping centers, metro, parking lots) require special fire safety measures, industrial facilities (warehouses, production workshops) should take into account the specifics of production, ventilation and logistics.
4. Economic and environmental aspects – reducing the cost of acquiring land plots by using underground space, minimizing the impact of construction on the urban landscape and the natural environment, using energy-efficient technologies, in particular, such as geothermal heating.
5. Safety and durability – Designing the structure as a whole and individual structures, taking into consideration long-term loads and aggressive conditions, integrating modern systems for monitoring the technical condition of structures, and ensuring stability.

The construction of residential, public, and industrial structures underneath the ground requires a thorough analysis of all factors that determine their safety, durability, and economic feasibility. Let us consider the main geological, geophysical, and hydrogeological factors that affect the underground construction of residential, public, and industrial facilities.

Geological conditions have a decisive influence on the choice of a site for the construction, design, and operation of underground structures. Successful underground construction is only possible with careful consideration of geological, geophysical, and hydrogeological factors.

Geological factors include, first of all, the lithological composition of rocks, namely the types of rocks, their strength, and stability. The composition, structure, and mechanical properties of rocks determine the state of the rock massif and the choice of construction methods and types of foundations.

Secondly, these are the tectonic features of the region – the presence of faults, dislocations, fractured zones, weakening zones, etc. The presence of faults, compression zones, and folded structures affects the mechanical properties of rocks, the stability of the base and structures, and the safety of engineering structures.

Thirdly, this is the seismicity of the area – the need to consider the seismic activity of the region and comply with the relevant building codes, taking into account the probability of earthquakes, their intensity, and frequency.

This list should also include engineering and geological processes – for certain areas, these are karst processes (the presence of karst cavities, the possibility of failures), subsidence, landslides, mudflows, which can complicate the construction and operation of structures.

Geophysical factors can be evaluated using geophysical methods that allow for the assessment of underground conditions without significant excavation. The most common are:

– evaluation of seismic stability, research of rock strength and homogeneity, voids and faults interpretation (seismic exploration) – the level of seismic activity of the region determines the need for special structural solutions to ensure the stability of buildings during earthquakes;

– detection of cavities and anomalous zones (gravimetry) – anomalies in the gravitational field can indicate different types of rocks and deep geological structures;

– determination of the depth of groundwater and the composition of rocks (electrical exploration) – the electrical conductivity of rocks helps to identify water-saturated zones, clayey rocks, and zones of reduced strength;

– detection of radioactive zones that can affect the ecology and safety of facilities (radiometric surveys);

– the magnetic field is used to detect magnetic rocks and determine structural features.

Hydrogeological factors – an important aspect is the presence and characteristics of groundwater. These are the occurrence depth and thickness of the aquifer, the direction of groundwater movement (possibility of flooding, impact on the foundation), the chemical composition of the water, and seasonal fluctuations in the groundwater level. The groundwater level affects the need for drainage systems and waterproofing. The flow rate of aquifers determines the risk of flooding and the complexity of drainage. Chemical composition of water – the aggressiveness of water can affect the corrosion of building materials. Flooding of the territory – the possibility of changing the water level under the influence of seasonal factors and construction work.

Having analysed the generally available engineering and geological factors (geological, geophysical, and hydrogeological conditions), one can conclude that all these factors should be divided, according to their influence, into two groups –favourable for underground construction and negative (unfavourable) (Table 1).

Below is a brief description of the influence of individual factors according to Table 1 on underground construction.

Table 1 – Distribution of main geological factors by nature of influence

No.	Negative (unfavourable) factors	Favourable factors
1.	Low strength and stability of soils and rocks	High strength and stability of soils and rocks
2.	Heterogeneity of the geological environment	Homogeneity (homogeneity) of the geological environment
3.	High seismic activity	Minimal seismic activity
4.	High tectonic dislocation	Simple tectonic structure
5.	High groundwater level	Low groundwater level
6.	High aquifer flow rate	Low aquifer flow rate
7.	Chemical composition of water – aggressive	Chemical composition of water – neutral
8.	Presence of karst formations and landslide zones	Presence of favorable geological structures or natural cavities
9.	Emission of harmful gases	Absence of harmful gases
10.	Depth is both a favourable and unfavourable factor	
11.	Environmental impact can be a favourable and unfavourable factor	

1. Strength and stability of soils and rocks. Strong rocks or stable soils provide a reliable foundation for structures. In regions with stable igneous and metamorphic rocks, construction is possible with minimal risks. Granite, limestone, or other stable rocks ensure the durability and strength of structures. Weak or unstable rocks (sands, clays, loams, karst formations) can cause subsidence, landslides, or collapses.

2. The homogeneity (uniformity) of the geological environment is a property of a geological massif, which is characterized by the absence of sharp changes in its composition, structure, and physical and mechanical properties. A homogeneous environment has a uniform mineralogical composition, similar porosity, permeability, strength, and other geological parameters within a certain volume, which greatly facilitates calculations and prediction in the behaviour of rocks under load. The absence of significant changes in the composition of soils and rocks subsequently facilitates construction and operation.

3. Minimal seismic activity reduces the risks of damage, deformation, and destruction from earthquakes during construction and operation. High seismic activity carries the risk of destruction during earthquakes. In areas of high seismic activity, strict standards must be observed, and earthquake-resistant structures must be used.

4. Tectonic structure of the territory. Tectonic structure can be complicated by numerous faults, both active and inactive, dividing the Earth's crust into separate blocks. Fractured zones are often weakened and prone to deformation. They can be characterized by high seismic activity due to the movements of tectonic plates and high intensity of seismic waves, which affects the stability of structures. Regarding dislocation, we are talking about both the presence of ruptures within the blocks and

developed fracture systems. The presence of fracture zones and mixed structures reduces the strength of rocks and makes it difficult to predict the mechanical behaviour of the soil. In such zones, active movement of groundwater can be observed, which can cause subsidence or a rise in the ground. Active geodynamic processes can take place – landslides, rockfalls, etc. The presence of folded structures (anticlines and synclines) can affect the stability of the soil and the location of structures. Deformation zones can also form, which complicates tunnelling and foundation work. Complexly dislocated zones are characterized by tectonic pressure and changes in the stress-strain state, which can cause high horizontal and vertical stresses in rocks, leading to sudden shifts. Local compression and tension zones are also possible, affecting the stability of underground facilities. Construction in areas of complex tectonic structure requires thorough engineering and geological research, special measures to strengthen soils and seismic protection of structures.

5. Groundwater level. A low groundwater level minimizes the need for waterproofing and drainage systems. A high groundwater level, on the contrary, can lead to flooding of underground structures, which requires additional engineering solutions. Such a groundwater level determines the need to use drainage systems and waterproofing measures. In areas with a high groundwater level, special drainage measures are required. It is also necessary to take into account the possible flooding of the territory, which depends on seasonal fluctuations in the groundwater level and the impact of construction work. Construction can alter natural drainage, leading to rising water levels and flooding. In some low-lying areas, seasonal rises in groundwater levels often lead to flooding of basements and underground utilities. To prevent this, construction should take into account seasonal fluctuations in water levels and provide drainage and waterproofing systems. Separately, the possibility of hydraulic communication between different groundwater horizons should be borne in mind.

6. Aquifer flow rate. The flow rate, or productivity of aquifers, determines the volume of water that can penetrate underground structures. High flow rates can complicate construction and operation due to the constant inflow of water. This requires the use of powerful pumping stations to drain water and ensure the safety of construction work.

7. Chemical composition of water. The chemical composition of groundwater affects the durability of building materials. Aggressive waters containing elevated concentrations of sulfates, chlorides, or other chemical compounds can cause corrosion of metal elements and destruction of concrete structures. For example, groundwater often contains a high concentration of sulfates, which can lead to sulfate corrosion of concrete structures. Therefore, sulfate-resistant cements and special protective coatings are used in the construction of underground structures in such conditions. The low aggressiveness of groundwater reduces corrosion of materials and destruction of structures.

8. The presence of natural cavities or favourable geological structures allows you to reduce the amount of excavation work. Karst and hollow formations carry the risk of soil subsidence or sudden collapse. The absence of karst formations and landslide

zones guarantees the stability of the storage facility and minimizes the risks of subsidence or destruction.

9. The accumulation of harmful gases (radon, methane, carbon dioxide) requires additional ventilation.

10. The depth of the facility can be both a negative factor and a favourable one. On the one hand, depth ensures the stability of the structure from external influences, and on the other hand, it leads to an increase in the cost of construction and further operation.

11. The impact on the environment of underground structures under certain conditions can be positive due to the preservation of the natural landscape of the earth's surface. On the other hand, there may be a violation of soil layers, a change in water balance, etc. Large volumes of excavated soil can complicate work and create problems with its disposal.

It is worth noting that depending on the construction site and the purpose of the structure, these factors may have a greater or lesser impact.

The principles of geological zoning of the territory for the selection of a site for underground construction should be based on the analysis of natural conditions and other factors that may affect the stability and safety of structures. In general, it is advisable to define the main principles as follows:

1. Tectonic analysis – determination of the presence of faults, fractured zones, zones of tectonic activity, and seismic hazards, considering the risk of neotectonic movements.
2. Lithological and stratigraphic analysis – the evaluation of the composition and thickness of rocks, their physical and mechanical properties, and determination of the presence of unstable or weathered rocks.
3. Hydrogeological conditions – study of the groundwater levels, their aggressiveness to construction materials, and the evaluation of the possible impact of groundwater on the stability of structures.
4. Engineering and geological characteristics – analysis of the bearing capacity of soils. Determination of possible deformation processes (subsidence, heaving, landslides, etc.).
5. Exogenous geological processes – identification of karst phenomena, landslides, mudflows, the evaluation of the territory’s susceptibility to landslides, flooding, and erosion.
6. Ecological and geochemical factors – analysis of possible contamination of groundwater and soil, the evaluation of radioactive background and gas concentrations (radon, methane).
7. Socio-economic aspects – assigned purpose of the structure, availability of infrastructure for construction and operation, compliance of the project with current building codes and regulations.

When choosing a site for underground construction, all these factors must be taken into account in a complex to ensure the safety, durability, and economic efficiency of the project.

The geological structure of Ukraine consists of structures of different ages and genesis, the rocks of which are represented by heterogeneous rock composition and age [17, 18]. The geological features of each structure have been studied separately for a considerable time. Special attention has been and continues to be paid to the Ukrainian Crystalline Shield (UCS), the rocks of which are represented by ultrametamorphic, intrusive-magmatic, and metasomatic formations. These rocks are characterized by high strength, which makes them suitable for placing underground facilities. Within the shield, the density of rocks is associated with a block structure, its values vary within 2.66–3.65 g/cm^3.

Given the general principles of zoning territories outlined above (including taking into consideration seismicity (Fig. 1)), in Ukraine, the most appropriate is to search for optimal areas for placing underground facilities within the Ukrainian Crystalline Shield.

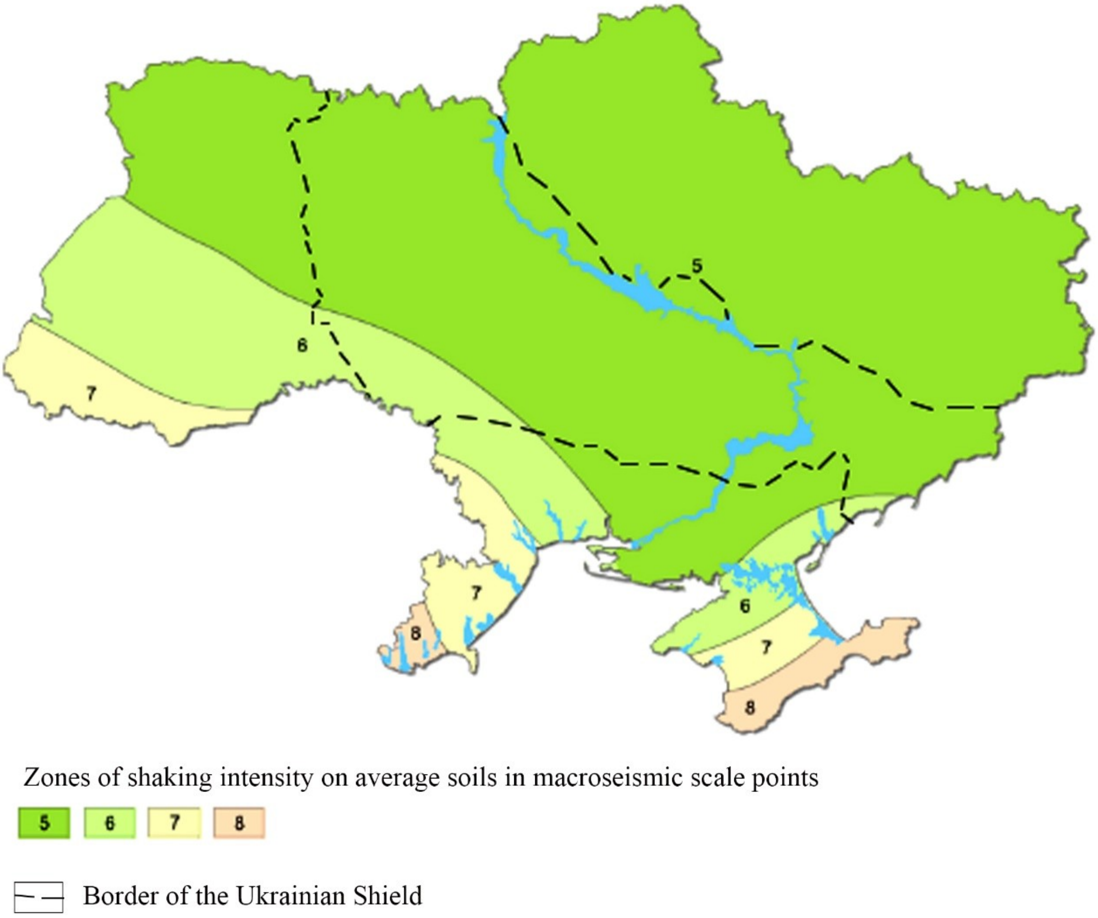

Figure 1 – The seismic zoning map of Ukraine [19]

In the context of considering the geological and geotechnical aspects of underground construction, it is advisable to refer to existing world experience. Namely, to the construction of large underground facilities in countries located on the Baltic Crystalline Shield. The Baltic Crystalline Shield covers the territories of several countries in Northern Europe. It includes: Sweden – a significant part of the country, especially its central and northern parts; Norway – the southern and central parts of the country; Finland – almost the entire territory of the country; Russia – the north western part, including Karelia and the Leningrad Region; Estonia – the northern part of the country, especially the areas where crystalline rocks outcrop. The Baltic Shield is one of the oldest geological structures in Europe, formed in the Archean and Proterozoic.

The Baltic Crystalline Shield and the Ukrainian Crystalline Shield have several common features in their geological structure, since both are parts of the ancient basement of the East European Platform. The main similarities between them are as follows:

1. Archean-Proterozoic basement. Both shields consist mainly of Archean and Proterozoic rocks that formed more than 2.5 billion years ago. The main rocks are gneisses, granites, quartzites, amphibolites and migmatites;
2. Tectonic stability. They are part of the stable part of the platform, having undergone only minor horizontal movements over the past hundreds of millions of years. There is an absence of significant folding deformations in the Phanerozoic era.
3. Deep faults and magmatism. Both shields are pierced by deep faults through which igneous rocks were supplied at different times. On their territory, manifestations of magmatism and metamorphism are recorded, in particular in the Paleoproterozoic and Neoproterozoic periods;
4. Ore content. Both shields are rich in minerals, in particular ore minerals. The Ukrainian shield contains iron, manganese, uranium, and rare earth ores, and the Baltic shield contains iron ores, nickel, copper, gold, and rare metals;
5. Depth of the basement. In both cases, the basement comes to the surface or lies under a small cover of sedimentary rocks, which distinguishes them from other parts of the platform.

Thus, the Baltic and Ukrainian crystalline shields have a common origin, similar tectonic features, and similar geological evolution.

Underground construction is developed in Norway due to the complex mountain terrain and stable crystalline rocks. Norway actively uses natural geological conditions to create underground infrastructure facilities, which increases their safety and efficiency. Here are some of the most famous underground facilities:

Transport tunnels – Lærdalstunnelen – is the longest road tunnel in the world (24.5 km), connecting Lærdal and Aurland, Atlantic Tunnel (Atlanterhavstunnelen) – is an underwater tunnel (5.7 km) between Kristiansund and the island of Averoy, Ryfylketunnelen – is the longest and deepest underwater tunnel (14.3 km, 292 m below sea level).

Hydroelectric power plants (HPP) and energy facilities – HPP Tiuni (Tunnsjødal Power Station), HPP Liotopen (Lysebotn II Power Station), HPP Mahasinnet (Mågeli Power Station).

Military and strategic sites – Olavsvern underground submarine base (Olavsvern Naval Base) – is a former military base dug into the rock, now used commercially, bunkers in the mountains of Norway – they are used as military and reserve storage.

Storage and scientific sites – Svalbard Global Seed Vault – it is located on the Spitsbergen archipelago, it is a global repository for seed samples in case of global disasters. Scientific laboratories in the mountains – they are used for climate, geophysics and security research.

Sweden also has a well-developed underground construction industry thanks to the stable crystalline rocks of the Baltic Shield. Sweden actively uses underground spaces for transport, energy, defense, and science, adapting geological conditions for efficient construction. The most famous underground facilities include transport tunnels, energy facilities, military bunkers, and scientific storage facilities:

Transport tunnels – Halmstad Tunnel (Hallandsåstunneln) – it is a railway tunnel (8.7 km), which improves the connection between Gothenburg and Malmö, Södertunneln – it is a tunnel in Stockholm for the city railway, an underwater tunnel through Öresund (Öresund Tunnel) – it is a part of the Öresund Bridge connecting Sweden and Denmark.

Hydroelectric power plants and energy facilities – HPP Hota (Göta Power Station – it is an underground power plant on the Göta Elv River, HPP Aker (Akkats Power Station) – it is a partially underground hydroelectric power plant in Lapland.

Nuclear waste storage facility CLAB (Central Interim Storage Facility for Spent Nuclear Fuel) – it is located in Oskarshamn, is used for the temporary storage of spent nuclear fuel.

Military and strategic facilities – Musko (Muskö Naval Base) – is an underground naval base dug into the granite rocks of the archipelago near Stockholm, Bunker "Viten" (Wittsjö Bunker) – is one of many Swedish military fortifications, underground command centers – they are used by the government and military for strategic purposes.

Repositories and scientific facilities – the nuclear waste repository in Forsmark (Forsmark Repository) – is a long-term nuclear fuel storage project, global data center in a mountain cave (Pionen White Mountains Data Center) – is an underground data center in Stockholm, located in a former military bunker, the research laboratory Aspö Hard Rock Laboratory – is used to study geological conditions for nuclear waste storage.

Finland has extensive experience in underground construction due to its geological features. Here are some of the most famous facilities.

The Onkalo underground nuclear waste repository is located on the island of Olkiluoto. It is the world's first deep geological repository for the final storage of spent nuclear fuel (about 430 m deep).

The "Vestmostranden" underground tunnel in Helsinki is part of the capital's extensive underground road system, which helps reduce surface traffic and improve logistics.

The "Paaänne" underground water supply complex is one of the longest water supply tunnels in the world (120 km), bringing clean water from Lake Paaänne to Helsinki.

Helsinki's underground shopping malls are often connected to the metro and other underground structures, such as the "Itis" or "Kamppi" complex.

The underground emergency government center is used to manage the country in case of emergencies – the exact location is not disclosed.

Underground sports complexes allow for efficient use of space and reduce heating costs, such as the ice rink in the Kalasatama district of Helsinki.

Finland actively uses underground space for various purposes, which is an important element of its urban planning and security.

Therefore, the experience of underground construction on the Baltic Crystalline Shield can be useful for underground construction on the Ukrainian Crystalline Shield (UCS) in many key aspects. This experience can become the basis for selecting promising sites and developing optimal technologies for tunnelling, reinforcement and sealing of underground structures in the UCS. Methods for strengthening fractured rocks, waterproofing solutions and technologies for monitoring the stability of the massif are especially useful.

In the geological structure of the territory in Ukraine, the Ukrainian Shield plays an important, and to certain extent even a decisive role [20]. It consists in the fact that the UCS not only occupies a central, pivotal position in the structure of the territory, but is the only reliable source of information regarding the composition and structure of the upper consolidated crystalline crust and the Early Precambrian geological history of the territory in Ukraine. It is here that the Lower Precambrian basement comes out to the day surface and is available for direct study. From here, based on geological drilling materials and geophysical data, information about the structure of the shield basement is extended to the neighbouring territories of its submerged occurrence or submerged part.

A detailed description of the geological structure of the Ukrainian Shield is given in [20]. The Ukrainian Shield is a large outcrop of crystalline basement rocks in the southern part of the East European Platform. It is part of the so-called Dnieper or Ukrainian-Voronezh geoblock of the platform basement. The total area on which the complexes of the basement rocks of the Ukrainian Shield have natural outcrops to the surface is about 140 thousand km^2, and together with the slopes within the boundaries limited by the so-called boundary thrusts, the shield covers about 260 thousand km^2.

The folded basement is dissected by meridional deep faults into several blocks that stand out in the relief. Currently, the most justified scheme is one that combines six megablocks: Volynskyi, Pobuzkyi, Buzko-Rosynskyi, Inhulskyi, Serednoprydniprovskyi i Pryazovskyi; Osnytsko-Mikashevytskyi volcano-plutonic belt and four intermegablock suture zones: Brusylivska, Holovanivska, Inguletsko-Kryvorizska and Orikhivsko-Pavlogradska [17].

The rocks are represented by ultrametamorphic, intrusive-magmatic, and metasomatic formations – amphibolites, gneisses, quartzites, migmatites, metabasites, crystalline schists, granites, plagiogranites, diorites. The crystalline basement rocks are partially covered by younger sedimentary rocks; in many places (mainly in river valleys and gullies) they come out to the day surface, where they are recorded as outcrops. Within the shield, the rocks lie above the modern erosion base. The highest absolute level is 347 m, recorded in the upper reaches of the Bug.

Geological zoning of the territory within (UCS) for site selection should be based on the analysis of all previously identified favourable and negative factors of underground construction and the existing geological, hydrogeological, and tectonic features of the region.

The following are proposed as the main principles of geological zoning within the UCS:

1. Tectonic analysis:

1.1 Identification of tectonic fault zones (both deep and surface) within large tectonic blocks to avoid construction in seismically active regions.

1.2 Analysis of neotectonic movements that may cause additional stresses in the rocks.

1.3 Identification of fractured zones that are less favourable due to possible rock instability – the UCS is represented by Precambrian crystalline rocks (granites, gneisses, crystalline schists), which usually have high strength, but may be fractured.

2. Lithological and petrographic features (zoning by types of crystalline rocks):

2.1 Monolithic granites, gneisses, amphibolites are promising for underground construction due to high strength and low permeability.

2.2 Contact metamorphism zones – they may have altered mechanical strength.

3. Hydrogeological conditions:

3.1 Determination of aquifers, groundwater levels and the presence of hydraulic communication between them. Most of the territory of the UCS is characterized by thin aquifers or their absence in massive crystalline rocks, which is an advantage for underground construction.

3.2 Determination of individual areas with increased fracturing, where groundwater can concentrate.

3.3 Evaluation of possible manifestations of underground drainage and aggressiveness of waters (especially in regions with sulfate-carbonate complexes [21]).

4. Engineering and geological characteristics:

4.1 Determination of the strength and stability of rocks to predict deformation processes.

4.2 Evaluation of the stress-strain state of the massif, especially in areas of tectonic faults.

4.3 Research on the risks of decompaction of the crystalline basement under the impact of man-induced load loads.

5. Exogenous geological processes:

5.1 Considering the risks of karst phenomena in areas where the UCS is covered by sedimentary sediments (for example, within the Dnieper-Donets depression).

5.2 Analysis of the territory's susceptibility to landslides, especially in zones of contact between crystalline rocks and sedimentary strata.

5.3 Monitoring the possible accumulation of gases (radon, methane) in cracks and caverns.

6. Ecological and man-made factors:

6.1 Analysis of the negative anthropogenic impact of underground construction on the environment, in particular on water bodies, fertile agricultural soils or forest lands, including protected ones. These factors can significantly restrict the choice of possible areas for underground construction sites.

6.2 Analysis of the negative anthropogenic impact on underground structures (the presence of mines, quarries, large engineering structures that can affect the state of the geological environment).

6.3 Evaluation of the natural background radiation level (granites and gneisses may have an increased concentration of uranium and thorium).

Geological zoning of the UCS allows you to determine the best conditions for safe and durable underground construction and provide recommendations for the site selection.

Optimal sites within the UCS are:

– large, least dislocated and stable blocks of the III^{d} order;

– areas with monolithic granites and gneisses with low fracturing;

– areas with minimal impact of fault zones and a stable geological environment;

– areas with low groundwater levels.

Undesirable sites are:

– zones of active tectonic faults, especially with modern seismic activity

– areas with high fracturing, karst processes, or zones of increased water saturation.

– areas with increased radiation background or significant man-made impact.

5. Conclusions

Geological factors for conducting underground construction, both favourable and negative, were identified and analysed. Their brief characteristics are presented. Given these factors, general principles of geological zoning of territories and, in particular, within the boundaries of the UCS are determined.

The most suitable areas for underground construction of public, industrial, and military facilities are areas of simple structure (the Ist category of complexity) according to engineering and geological conditions. Namely:

– territories with a low level of seismicity;

– areas with monolithic strong rocks (granites and gneisses);

– territories with a stable geological environment, minimal impact of fault zones and non-fractured rocks, or rocks with low fracturing;

– areas with stable hydrogeological conditions and a low level of non-aggressive groundwater.

The authors analysed the underground construction experience of countries (Sweden, Norway, Finland) located within the Baltic Crystalline Shield and proved the general similarity of the structure and geological conditions of the Baltic Shield and the Ukrainian Crystalline Shield.

It was also concluded that in Ukraine, the most expedient is to search for optimal sites for placing underground facilities within the Ukrainian Crystalline Shield.

The choice of the facility's location should be made taking into account its specific intended purpose and requirements under building rules and regulations.

Conducting comprehensive geological and geophysical studies will enable a generalization of the structure of promising sites and ultimately justify their selection. Justifying the final selection of sites requires a detailed examination of all available geological and geophysical information regarding the structure of the sites under consideration, the execution of appropriate geophysical work to detail the sites' structure and the properties of the rocks, drilling wells for further engineering and geological surveys, and directly conducting engineering and geological surveys.

Conflict of interest

Author states no conflict of interest.

REFERENCE

1. Ministry of Regional Development and Construction of Ukraine (2014), *DBN A.2.1-1:2014 Inzhenerni vyshukuvannia dlia budivnytstva* [DBN A.2.1-1:2014 Engineering surveys for construction], Ministry of Regional Development and Construction of Ukraine, Kyiv, Ukraine.

2. Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine (2018), *DBN B.1.2-14:2018. Zahalni pryntsypy zabezpechennia nadiinosti ta konstruktyvnoi bezpeky budivel i sporud* [DBN B.1.2-14:2018. General principles of ensuring reliability and structural safety of buildings and structures], Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, Kyiv, Ukraine.

3. Ministry of Regional Development of Ukraine (2014), *DBN A.2.2-3:2014. Sklad ta zmist proektnoi dokumentatsii na budivnytstvo* [DBN A.2.2-3:2014. Composition and content of design documentation for construction], Ministry of Regional Development of Ukraine, Kyiv, Ukraine.

4. Ministry of Regional Development and Construction of Ukraine (2014), *DBN V.1.1-12:2014. Budivnytstvo u seismichnykh raionakh Ukrainy* [DBN B.1.1-12:2014. Construction in seismic areas of Ukraine], Kyiv: Ministry of Regional Development and Construction of Ukraine, Kyiv, Ukraine.

5 Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine (2017), *DBN V.1.1-45:2017. Budivli i sporudy v skladnykh inzhenerno-heolohichnykh umovakh. Zahalni polozhennia* [DBN B.1.1-45:2017. Buildings and structures in complex engineering and geological conditions. General provisions], Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine, Kyiv, Ukraine.

6. Ministry of Regional Development and Construction of Ukraine (2017), *DBN V.1.1-46:2017. Inzhenernyi zakhyst terytorii, budivel i sporud vid zsuviv ta obvaliv. Osnovni polozhennia* [DBN B.1.1-46:2017. Engineering protection of territories, buildings and structures from landslides and rockfalls. General provisions], Ministry of Regional Development and Construction of Ukraine, Kyiv, Ukraine.

7. Ministry of Regional Development and Construction of Ukraine (2011), *DSTU B V.2.1-28:2010 Inzhenerni vyshukuvannia dlia budivnytstva. Osnovni polozhennia* [DSTU B V.2.1-28:2010. Engineering surveys for construction. General provisions], Ministry of Regional Development and Construction of Ukraine, Kyiv, Ukraine.

8. Ministry of Regional Development and Construction of Ukraine (2011), *DSTU-N B V.1.1-27:2010 Zakhyst vid nebezpechnykh heolohichnykh protsesiv, shkidlyvykh ekspluatatsiinykh vplyviv, vid pozhezhi. Budivelna klimatolohiia* [DSTU-N B V.1.1-27:2010. Protection against the dangerous geological processes, harmful operational nfluences, and the fire. Building climatology], Ministry of Regional Development and Construction of Ukraine, Kyiv, Ukraine.

9. Ministry of Regional Development and Construction of Ukraine (2024), *DSTU 9275.1:2024 Nastanova z vykonannia inzhenernykh vyshukuvan dlia budivnytstva. Chastyna 1. Inzhenerno-heolohichni vyshukuvannia* [DSTU 9275.1:2024. Guidelines for conducting engineering surveys for construction. Part 1: Engineering and geological surveys], Ministry of Regional Development and Construction of Ukraine, Kyiv, Ukraine.

10. Eurocodes: Building the future (2024), "EN 1997-1:2004 Eurocode 7: Geotechnical design - Part 1: General rules", available at: https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-7-geotechnical-design (Accessed 03 October 2024).

11. Ministry of Regional Development of Ukraine (2010), *DSTU-N B EN 1997-1: 2010. Eurocode 7. Geotechnical design. Part 1. General rules EN 1997-1* [Eurocode 7. Geotechnical design. Part 1. General rules *EN 1997-1*], Ministry of Regional Development of Ukraine, Kyiv, Ukraine.

12. Ministry of Regional Development and Construction of Ukraine (2011), *DSTU B V.1.1-28:2010 Zakhyst vid nebezpechnykh heolohichnykh protsesiv, shkidlyvykh ekspluatatsiinykh vplyviv, vid pozhezhi. Shkala seismichnoi intensyvnosti [DSTU B V.1.1-28:2010. Protection against hazardous geological processes, harmful operational impacts, and fire. Scale of seismic intensity],* Ministry of Regional Development and Construction of Ukraine, Kyiv, Ukraine.

13. Zotsenko, M.L., Kovalenko, V.I., Yakovlev, Petrakov, O.O., Shvets, V.B., Shkola, O.V., Bida, S.V. and Vynnykov, Yu.L. (2003), *Inzhenerna heolohiia. Mekhanika gruntiv, osnovy i funda*menty [Engineering geology. Soil mechanics, bases and foundations], Poltava National Technical University, Poltava, Ukraine.

14. Luchko, Y.Y. (2013), *Gruntoznavstvo, mekhanika gruntiv, osnovy ta fundamenty* [Soil science, soil mechanics, bases and foundations], Kameniar, Lviv, Ukraine.

15. Borzyak, O.S., Trykoz, L.V. and Herasymenko, O.S. (2017), *Inzhenerna heolohiia* [Engineering geology], UkrDUZT, Kharkiv, Ukraine.

16. Borziak, O.S., Liutyi, V.A., Romanenko, O.V. and Podtelezhnikova, I.V. (2022), *Inzhenerno-heolohichni doslidzhennia dlia budivnytstva* [Engineering and geological surveys for construction]. UkrDUZT, Kharkiv, Ukraine.

17. Kostenko, M.M. and Shutenko, L.M. (2018), “Problematic issues of geotectonic zoning of the Ukrainian Shield basement and ways of solving them”, *Mineral Resources of Ukraine*, vol. 2, pp. 21–29.

18. Ministry of Environmental Protection of Ukraine, State Geological Service and Ukrainian State Geological Survey Institute (2007), *Tectonic map of Ukraine. Scale 1:1,000,000. Explanatory note*, UkrDGRI, Kyiv, Ukraine.

19. *Karty Ukrainy (2024), Seismichne raionuvannia Ukrainy* [Geomap Ukraine, n.d. *Seismic zoning map of Ukraine*], Available at: https://geomap.land.kiev.ua/zoning-16.html (Accessed 03 October 2024).

20. Ministry of Environmental Protection of Ukraine, State Geological Service, Ukrainian State Geological Survey Institute and Ivan Franko National University of Lviv (2007), *Tektonichna karta Ukrainy. Masshtab 1:1000000. Chastyna II. Tektonika fundamentu Ukrainskoho shyta. Masshtab 1:2000000. Poiasniuvalna zapyska* [Tectonic map of Ukraine. Part II: Tectonics of the Ukrainian Shield basement. Scale 1:2,000,000. Explanatory note], UkrDGRI, Kyiv, Ukraine.

21. Suiarko, V.H., Velychko, V.M., Havryliuk, O.V., Sukhov, V.V., Nyzhnyk, O.V., Biletskyi, V.S., Matvieiev, A.V., Ulitskyi, O.A. and Chuiienko, O.V. (2019), *Inzhenerna heolohiia (z osnovamy heotekhniky)* [Engineering geology (with fundamentals of geotechnics)], in Suiarko, V.H (ed.), V.N. Karazin Kharkiv National University, Kharkiv, Ukraine.

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ГЕОЛОГІЧНІ АСПЕКТИ БУДІВНИЦТВА ПІДЗЕМНИХ ОБ’ЄКТІВ В УКРАЇНІ

Безручко К.А.

Анотація. Підземне будівництво набуває дедалі більшого значення в умовах зростаючої урбанізації, дефіциту вільних територій та необхідності збереження природного середовища. Зведення житлових, громадських та промислових споруд під землею вимагає ретельного аналізу геологічних, геофізичних і гідрогеологічних умов, що визначають їхню безпеку, довговічність і економічну доцільність. Розглядаються основні геологічні, геофізичні та гідрогеологічні фактори, що впливають на підземне будівництво житлових, громадських та промислових об'єктів. Оцінено їхній вплив на вибір місця будівництва, конструктивні особливості та безпеку об'єктів. Розглянуто методи дослідження підземного простору та наведено рекомендації щодо мінімізації ризиків. Визначені та проаналізовані геологічні чинники щодо ведення підземного будівництва, як сприятливі, так і негативні. Наведена їх стисла характеристика. З огляду на ці чинники, визначені загальні принципи геологічного районування територій та, зокрема у межах УКЩ. Найбільш придатними для підземного будівництва громадських, промислових та воєнних об’єктів є ділянки простої будови (І-ої категорії складності) за інженерно-геологічними умовами. А саме території з низьким рівнем сейсмічності; райони з монолітними міцними скельними породами (гранітами та гнейсами); території з стабільним геологічним середовищем, мінімальним впливом розломних зон та нетріщинуватими породами, або породами з низькою тріщинуватістю; області зі стабільними гідрогеологічними умовами та низьким рівнем неагресивних підземних вод. Проаналізовано досвід підземного будівництва країн (Швеція, Норвегія, Фінляндія), розташованих у межах Балтійського кристалічного щита. Доведена загальна схожість будови та геологічних умов Балтійського щита та УКЩ. Визнано, що в Україні найбільш доцільним є пошук оптимальних ділянок для розміщення підземних об’єктів у межах Українського кристалічного щита. Остаточний вибір місця розташування об’єкту має відбуватися з огляду на його конкретне цільове призначення та вимог до нього відповідно до будівельних правил та норм.

Ключові слова: підземне будівництво, геологічні фактори, гідрогеологія, інженерна геологія, геофізичні дослідження, Український щит.