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PROGNOSTIC ASSESSMENT OF HAZARDOUS GEODYNAMIC PROCESSES IMPACT ON UNDERGROUND CONSTRUCTION IN THE CENTRAL PART OF LVIV

The purpose of this research is to conduct a predictive assessment of the impact of hazardous geodynamic processes on underground construction in the central part of Lviv. These processes are linked to specific geological structures, hydrogeological conditions, unique rock properties, and the chemical composition of groundwater. Relevance of work. In Lviv and many other large cities in Ukraine, transportation and parking problems are extremely acute. They are especially relevant for the central part of the city, which is characterised by a dense network of narrow streets, extreme vehicle saturation, dense buildings, and numerous transportation attractions. Their design and construction require detailed information about the structure, composition, and properties of the geological environment, as well as the geological risk assessment associated with the construction and operation of such structures. Research methods. Information on geological conditions, composition, physical, mechanical, filtration, and corrosion properties of soils, the aggressiveness of groundwater, design features of structures, types of foundations, and experience in constructing underground trams has been collected and comprehensively analysed. More than 50 experimental wells were specially drilled, and geophysical, engineering, geodetic, and laboratory studies were performed. Computer cartographic models of the geological environment were also built. Results. Based on the data obtained, the geological structure, hydrogeological conditions, physical and mechanical properties of the soils, and morphodynamic processes in the central part of the city are characterised. A spatial analysis of the risk-forming components of the geological environment is conducted, and the risks associated with its construction development are assessed. Scientific novelty. Various types of risk-forming factors for underground construction in the central part of Lviv have been identified. These factors include: geological factors that encompass structure of the rock massif, composition and condition of the rocks, their physical, mechanical and seismic properties, as well as their vulnerability to external influence; hydrogeological factors that involve the number of aquifers, depth of groundwater, their chemical composition and aggressiveness toward building structures, pressure level and the relationship between aquifers; morphodynamic factors that relate to the speed of modern tectonic movements and the development of suffosion processes and deformations of the Earth's surface. For the first time, a predictive assessment of geological risks associated with underground construction in various areas of the study region has been provided. Practical significance. The results obtained will make it possible to ensure the rational spatial location of underground parking lots and other objects of underground urbanization, to choose effective construction technologies that provide minimal risks for the stability of the designed structures and adjacent buildings and engineering infrastructure and will also serve as an information base for predicting the negative consequences of the construction and operation of underground structures in the long term.

Keywords: underground urbanism, relief, technogenic soils, organic soils, quicksand, groundwater, physico-mechanical, and seismic properties of soils, geological risks, dangerous geodynamic processes.

Introduction

The intensive development of large cities is accompanied by the aggravation of several socio-economic, spatial-territorial, transport, and environmental problems.

This is especially true for cities with difficult natural conditions and a long history of existence. Lviv is a large administrative centre with over 750,000 people in the western region of Ukraine (Fig. 1).

The solution to these critical and urgent problems puts the comprehensive development of underground space on the agenda. Lviv also belongs to the category of cities that are especially in need of underground construction, primarily its historical part, which is characterised by dense buildings, extreme transport concentration, and acute environmental problems. These problems include excessive pollution of the atmospheric air, soil cover, and groundwater. Additionally, there is a risk of flooding, suffosion processes, and the presence of many deformed structures, including architectural monuments.

Fig. 1. Lviv on the geographical map of Europe.

The underground space of Lviv has been used for a long time. Nature and methods of its use evolved with the development of the city, the improvement of its infrastructure, the operation of various modes of transportation, and changes in management methods. The development of the underground space of the central part of the city began, probably, from the time of the construction of stone residential and public buildings with basements. The depth of their floor was 2–3 m below the surface of the earth. Such premises (crypts) were arranged in many religious buildings. Deep cellars also existed in fortifications. Another direction in underground space development was the construction of water pipes, the first mention of which dates to the first half of the thirteenth century.

Later, sewer networks were constructed, with the most significant of these being the Poltva sewer collector. Construction began in 1839 and took nearly 50 years to complete. Near the Opera House, the collector is located at a depth of approximately 8 meters, just 1.6 meters away from the building's foundations. It features an underground structure with a cross-section of almost 20 m^2, built under complex engineering and geological conditions. An extensive network of underground water pipes, electrical and telephone lines, sewerage systems, and heating networks was also laid.

In the 1970s and 1980s, two underground pedestrian crossings were constructed at Mytna and Halytska squares. In recent years, several underground parking lots have been built beneath various buildings, including the "Rius" hotel and office center (located at Akademika Hnatiuka str., 12A), the shopping and entertainment center "Forum" on Dzherelna Str., and the unfinished "Golden Lion Hotel" on Teatralna Str. (adjacent to the "Dobrobut market"). Except for the parking lot under the unfinished "Golden Lion Hotel", these parking facilities have a depth of only 2 to 4 m.

This relatively shallow foundation depth minimizes the impact on the geological environment, thereby reducing risks associated with their construction and operation. The most ambitious project for underground development in Lviv is the attempt to build a high-speed underground tram.

Conceptual ideas for the large-scale development of the underground space of Lviv, primarily the construction of high-speed underground tram lines, were outlined in the "Comprehensive scheme of prospective development of all types of urban transport" (1975). [Lyubytskyi, 2018]. These ideas were specified in the project "Technical and Economic Foundations of the Construction of an Underground Tram" and included in the "Scheme for the Use of Underground Space in Lviv" (1981). This scheme not only proposed the construction of a high-speed underground tram but also envisioned a variety of other underground urban developments, including garages, subterranean passages, highway tunnels, cinemas, and catering establishments.

The technical design of the first stage of the tram's underground section was developed by the Kharkiv-metroproekt Institute, with a total tunnel length of 5.5 km and an average depth of 30 m from the ground surface [Lyubytskyi, 2018]. The construction of the first mine shaft, with a diameter of 5.0 m, began in the courtyard of the Potocki Palace. A significant decrease in the level of the Quaternary aquifer, which is hydraulically connected to the Upper Cretaceous layer, led to the formation of a depression funnel covering a substantial portion of the Lviv basin. This situation caused multi-scale dewatering and compaction of organic-mineral soils, resulting in deformation damage to nearly a hundred buildings and structures of varying degrees.

Cracks up to 30 cm wide formed in the load-bearing structures of the Potocki Palace, located near the mine shaft. This posed a serious threat to the integrity of the architectural monument, which is of national importance. Consequently, construction of the tunnel was suspended, and the implementation of this large-scale project, vital not only for Lviv but also for Ukraine, has been entirely halted and remains unresolved to this day.

The above clearly shows the crucial importance of the geological environment's structure, composition, and properties when selecting locations for underground construction projects. Additionally, these factors play a vital role in determining the technologies used for construction work, ensuring the stability and functionality of buildings, and creating environmentally friendly living conditions for residents.

Despite the negative experience of constructing a high-speed underground tram, the need for underground construction in the historical part of Lviv remains extremely acute. Its essence lies, first, in the excessive number of cars placed here. According to the regional road administration, more than 7,500 cars are waiting for parking in the city centre, concentrated in an area of approximately 1.5 km². The solution to this problem is envisaged by constructing several underground multi-level parking lots. Plots on Universitetska str., 1, Baturynska str., Voronoho str., Vitovskogo str., and the intersection of Kopernika – Stefanyka str., as well as Petrushevych and Mickiewicz sq., are being actively discussed. For many of them, historical and urban planning justifications for the planned construction have been developed. Unfortunately, there is still no assessment of the potential geological risks associated with such large-scale construction. The total share of underground structures in Lviv and Ukraine remains negligible.

The analysis of foreign experience in the development of underground space in large cities reveals that optimal conditions for ensuring sustainable development and comfortable living are achieved with a share of underground objects in the range of 25–30 % of the total area of existing surface structures [Kril, 2019b]. For the largest Ukrainian cities, this figure is only 3–5 %. The current situation indicates excellent prospects for developing the underground geospace of Ukrainian cities.

Underground structures and the geological environment together create a complex and dynamic system. The individual components of this system, both natural and human-made, have a significant influence on one another. The impact of these interactions is largely determined by the stability, economic viability, operational suitability, and environmental effects of the structures, as well as the construction activities.

As a result, selecting the spatial location of underground facilities, determining the appropriate depth of excavation, and preventing potential emergencies during both the construction and operation phases require a thorough investigation. This includes studying the structure, composition, and properties of the geological environment in the central part of Lviv, as well as assessing the geological risks associated with underground construction within its boundaries.

Review of literature sources

The development of underground space is a complex problem, the study of which falls within the field of view of scientists from various professional fields, including architects, urban planners, miners, and geologists. It has been most thoroughly worked out by a team of researchers from Igor Sikorsky Kyiv Polytechnic University, in particular [Gaiko, 2014; 2018, Gaiko, Kril, 2015; Gaiko, Matviychuk, 2020; Gaiko i in., 2015, 2018; 2019; Pankratova et al., 2018, 2020]. The fundamental work [Kravets et al., 2024] addresses general issues related to the development and utilization of underground city space, as well as the features of engineering and geological exploration, principles of planning, design, and construction of urban underground structures serving various purposes.

The paper [Pankratova et al., 2018] presents a systematic approach to the development of underground space, enabling informed decisions on the expediency of utilising the geological environment, considering multifactorial risks. Additionally, a morphological model for assessing the construction sites of underground facilities, developed by the authors, is presented. The paper [Gaiko et al., 2018] presents the author's typification methodology for the geological environment, which classifies it according to the favourability of development using GIS technologies. The scheme of the deep-functional section of the geological environment based on the allocation of characteristic emergencies and features of engineering and geological conditions and processes is presented in scientific papers [Kril, 2019a, 2019b]. Architectural and environmental aspects of underground urbanism of cities are considered in the following publications [Chepurna, 2017; Rindyuk, Maksymenko, 2020; Kofanov, Kofanova, 2021; Koznarska, 2023; Serdyuk, Kosakivskyi, 2024]. Such studies as [Voloshyn, 2001, 2002, 2004, 2010; Voloshyn, Pavlun, 2019; Voloshyn et al., 2020; Bogucki et al., 1993] present features of geological structure, hydrogeological conditions, composition, physico-mechanical, filtration properties of soils, aggressiveness of groundwater, development of morphodynamic processes, as well as engineering, geological, and geoecological problems in the central part of Lviv. A wide range of issues related to underground engineering and planning of underground space in cities is considered in numerous publications by foreign scientists [Gilbert P. H. et al., 2013; Gilbert P. H., 2014; Sterling, R. et al., 2012; Vähäaho, I., 2014]. In general, the challenges of developing underground space, particularly in regions like Lviv and its central area, have not been sufficiently examined. This necessitates further comprehensive research, considering the current nature and intensity of technogenic load.

Purpose and objectives of research

The purpose of this research is to predict the impact of hazardous geodynamic processes on underground construction in the central part of Lviv, taking into account the geological structure's peculiarities, hydrogeological conditions, specific rock properties, and the chemical composition of groundwater. The achievement of this goal is expected by solving the following main tasks:

− study of the geological structure and tectonics of the site;

− clarification of the conditions of occurrence of soils of different age, genesis, and lithological composition, identification of spatial patterns of their distribution;

− study of the composition, condition, physico-mechanical, filtration, corrosion, and seismic properties of soils, as well as the chemical composition of groundwater;

− determination of the direction and speed of vertical movements of the Earth's surface;

− identification of patterns of distribution, conditions, and depth of aquifers, hydraulic connection between them, head value, and direction of groundwater movement;

− forecast of changes in soil properties and hydrodynamic characteristics of groundwater under the influence of the construction of underground structures;

− separation of risk-forming factors by nature and intensity of impact on underground construction;

− predictive assessment of geological risks in developing the city's underground space.

Research methods

To gather information about the geological environment essential for developing project proposals in the central part of the city, a comprehensive series of field and laboratory studies was conducted. This included engineering and geological surveys, well drilling, mining tunneling, experimental filtration work, geophysical research, geodetic observations, and analysis of soil composition, condition, and physical, mechanical, and seismic properties, as well as the chemical composition of groundwater.

The engineering and geological survey was performed primarily to assess the extent of damage to buildings and structures in the central areas of the city and their spatial distribution. Drilling wells was aimed at:

− studying geological structure and hydrogeological conditions;

− sampling of soils and groundwater;

− conducting research, filtration, and geophysical research.

Geophysical surveys (gamma-gamma and neutron-neutron logging) were conducted to investigate the natural moisture and density of artificial soils in the aeration zone. Vertical electrical sensing made it possible to obtain data on the corrosive properties of soils. Geodetic observations were carried out to quantitatively assess the deformations of the Earth's surface and engineering structures by performing high-precision (Class II) levelling of the observation points network established by Ukraine's Main Department of Geodesy and Cartography. The obtained data were compared with the results of levelling from the Main Department of Geodesy and Cartography of 1974 and those of Polish researchers from 1934 and 1867 [Voloshyn, 2002].

Laboratory studies enabled the collection of data on the lithological composition, water-physical, physical, and mechanical properties of soils, as well as the chemical composition and aggressiveness of groundwater. The requirements of the current regulatory documents were carried out in the tests.

All lithological and stratigraphic-genetic soil complexes within the sphere of influence of the designed underground structures were studied. The requirements determined the Seismic properties of soils [State Building Standards (DBN), 2014].

The data obtained were processed using computer technologies.

Research results

Relief. From a geomorphological perspective, the central part of the city is situated within the Lviv basin, a deep, trough-like erosion depression formed by the valley of the Poltva River and its tributaries, extending in a sub-meridional direction for almost two kilometres (Fig. 2) [Voloshyn, 2001].

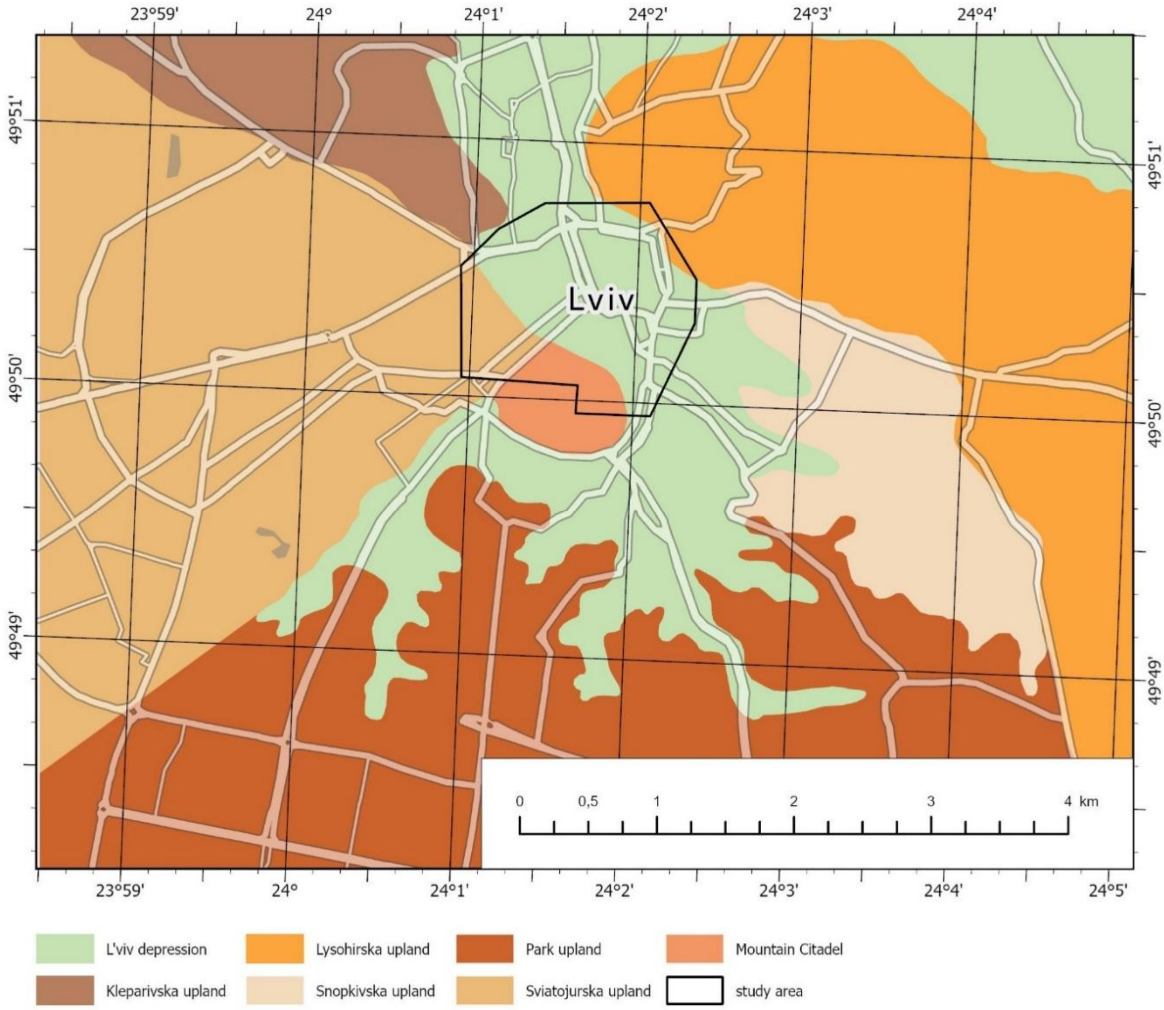

Fig. 2. Geomorphological map of the historical part of Lviv.

In the north, around Vysokyi Zamok Mountain, the hollow cuts the hilly ridge of Lviv Roztochchia. In the south and southeast, it borders the uplands of Snopkivska and Lychakivska, and in the east, it borders the Lysohirska uplands. From the northwest and west, it is bounded by the Kleparivska and Svyatoyurska uplands, and in the southwest by Mount Citadel.

The bottom of the basin is a flat-bottomed, mainly floodplain terrace of the Poltva and partially of the Pasika. Its width varies from 500–600 m to 800 m or more.

The modern surface of the floodplain is relatively flat, with a slight slope towards the Poltva Riverbed (near Shevchenko and Svoboda avenues). Absolute marks vary from 280.0–285.0 m in the tidy areas of the basin to 275.0–280.0 m in its riparian part. There is also a slight surface slope along the canalised bed of the river Poltva. Absolute marks decrease from 280.0 m in Hrushevskoho str. to 275.0 m around the Opera and Ballet Theatre.

In many places, there is a pronounced asymmetry in the transverse profile of the valley. In the Mount Citadel area, the depression's left slope is steep

(20−25°), while the opposite is relatively gentle. From Kopernika str. to Shevchenko str., this slope is gentle (3−8°), while the opposite slope is quite steep, and is up to 20° and more.

Due to the peculiarities of the geological structure, there is a significant diversity of slope morphology. They are predominantly straight and convex on the left side of the basin. The slopes of the right side are characterised by pronounced terracing. It is due to the presence of layers of sandstone and limestone in the geological section that are resistant to weathering. The research area's lowest terrace level is located between Krakivska and Pidvalna Streets. The absolute surface marks vary from 281.0 m to 285.0 m. The next, higher level with absolute heights of 293.0−295.0 m, is between Pidvalna and Lysenko Streets.

The basin is also characterised by pronounced altitudinal asymmetry. The relative elevations of watershed areas above the basin bottom in the west and south range from 30 m to 60 m. In the northeast and east, they reach 80−110 m.

The relief of the studied area has undergone significant changes throughout the city's history. Essentially, there is no natural relief in this region. Instead, a continuous layer of technogenic soils, known as the cultural layer, exists with a thickness ranging from 2 to 3 m up to 6 to 9 m. Additionally, the defensive ditches of fortifications, which reached depths of up to 8.0 m, have also been filled in. Buildings of various ages in this part of the city cover the floodplain of the Poltva River and the steep slopes of the valley.

Tectonics. From a geological structural perspective, the territory of Lviv is situated on the southwestern edge of the East European Platform, within the Lviv Cretaceous Mould. According to research data [Bogucki et al., 1993], three subparallel tectonic zones have been identified within the city's territory: the Eastern – Lysynytska, Central – Zubrivska, and Western – Stavchansko-Vereshchytska zones. These tectonic zones are a series of backstage-like gaps of north-western extension, which in many places are complicated by low-amplitude transverse displacements of the landslide type. One of the significant tectonic disturbances extends north-westward along the entire Lviv basin, dividing it into two separate blocks.

To obtain data on the deformations of the earth's surface in the studied area, high-precision (class II) levelling, analysis, and comparison of the data obtained with the results of similar measurements were per-formed by Polish (1887, 1914, 1934) and Ukrainian researchers (1974, 2001) [Voloshyn, 2002]. The study revealed both positive and negative deformations in the area examined. Different displacement surfaces are localized in specific locations. The majority of damaging events were observed in the riparian zone of the canalized Poltva River, with positive deformations occurring primarily along the river's marginal sections and the slopes of the surrounding basin. The average rate of surface subsidence from 1974 to 2001 was 2.4 mm, with a corresponding uplift of 1.2 mm per year.

The results of high-precision levelling performed in 1887, 1914, and 1934 also indicate significant displacement of the Earth's surface. The rate of surface subsidence is, on average, 1.5 mm per year, while the rate of rise is 1.3 mm per year. Comparisons of the deformation rate in the pre-war period and from 1974 to 2001 showed that surface subsidence over the past 27 years has increased by a factor of 1.6. In the central part of Lviv, which covers a small area (approximately 1.5 km²), multipolar deformations may indicate a polygenetic origin. Displacements of the Earth's surface with positive signs are primarily associated with the development of modern tectonic movements. In contrast, negative ones are related to natural factors, such as the presence of weak soils, technogenic, or peaty soils. In some areas, the absolute values of negative displacements have exceeded 354 mm in recent periods, which poses a critical risk-forming factor. This should be considered during underground construction.

Geological structure and properties of soils. In the central part of the city, there is a complex of soils variegated in lithological composition and properties, which includes technogenic accumulations (cultural layer), deposits of the Quaternary system, Neogene, and Upper Cretaceous (Fig. 3, 4) [Voloshyn, Pavlun, 2019, Voloshyn et al., 2020].

The soils of the cultural layer cover the territory of the historical part of Lviv in a continuous layer. Its thickness varies widely, from 2−3 to 6−9 m (Fig. 5) [Voloshyn, 2017]. On the slopes of the basin, it typically ranges from 3 to 4 m, on average, while in the floodplain of the river, particularly near its bed, it can reach heights of 7−9 m in some areas. A significant increase in capacity up to 6−8 m is also noted in the valleys of the flooded tributaries of the Poltva River, in particular, the river Bila (Knyazya Yaroslava Osmomysla str.), the Ortysh Stream (Pidvalna str., Valova str., Halytska sq.), defensive ditches (Svobody Ave., Valova str., Pidvalna str., L. Ukrainky str.), as well as the bastions of the Behrens Defence Belt (P. Rymlyanyna str., Darwin str., M. Kryvonosa str., etc.). Considering the specifics of sedimentation, natural and anthropogenic components are distinguished in the composition of the soils of the cultural layer. The natural component is represented by various lithological types of natural soils, which, as a rule, form the bulk and are closely related to the geological conditions of the territory. Different types of human waste products form the anthropogenic component. These are mainly construction materials (broken brick, natural stone, plaster, concrete fragments, separate stone, and wooden structures) and household waste (ceramics, glass, leather, animal bones, manure, metal, and non-metallic products). Additionally, there is industrial waste (ash, slag, moulding sands, etc.).

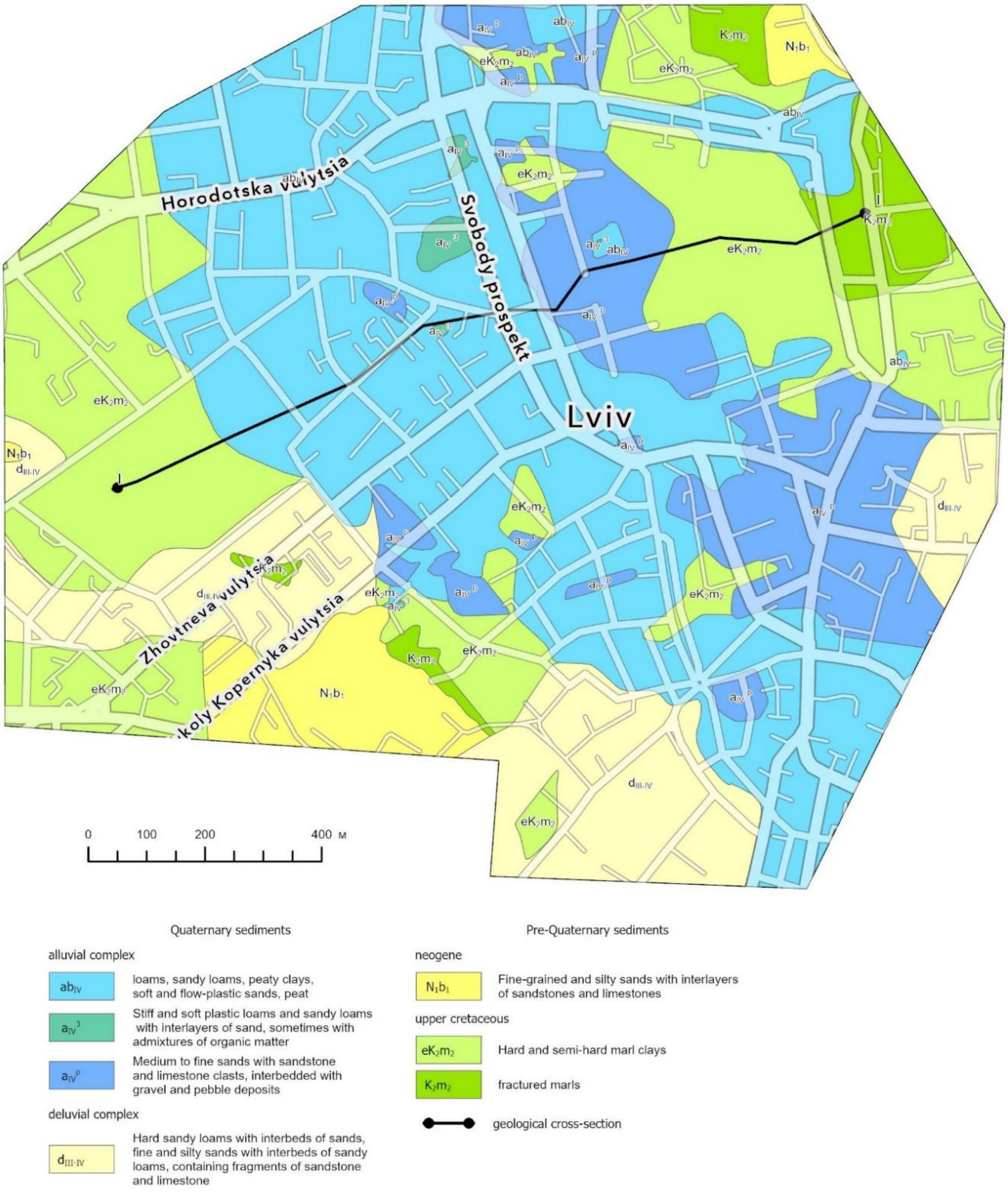

Fig. 3. Geological map of the central part of Lviv.

Individual layers are characterised by a lenticular-lingual, finely layered structure with frequent changes in lithological composition both in plan and depth. In the lower part of the thickness, household waste predominates. There are many more broken bricks and construction waste in the upper area (2.0–3.0 m). The identified patterns suggest that the defensive ditch served as a dumping ground for household and construction waste for a considerable period after it lost its intended purpose.

In many places of the study area, several “macro-inclusions” were also found, such as dismantled parts of foundations, remains of underground passages, basements, non-working sewer collectors and water pipes, buried cesspools, slurries, wells, wooden floors, paving stones, wooden piles, beds, etc., which give the thickness an exceptional heterogeneity. Organic matter plays a special role in the culture layer. It imparts a specific brownish-grey and dark grey colour, and determines the physical, mechanical, seismic, and corrosion properties of the water. In its composition, it is necessary to distinguish between finely dispersed humus-like and “macroorganic” components, such as remains of wooden buildings, piles, flooring, leather, etc. Finely dispersed organic matter is found almost everywhere and is caused not only by the accumulation of human waste products, but also by the permanent development of pedogenesis processes. Its content ranges from 2–5 % to 73 % and increases significantly in depth. The amount of organic matter, especially macroorganic matter, largely depends on the air and humidity regime of the strata, which in turn is closely related to the conditions of its occurrence and soil composition. The analysis of numerous sections of wells showed that technogenic soils are almost everywhere in the aeration zone on the slopes of the Lviv basin. The average value of the water saturation coefficient is 0.76. It is located both in the aeration zone and below the water level. Areas where soils are submerged are confined to zones of anthropogenic flooding, which occupy 23.4 % of the total research site area.

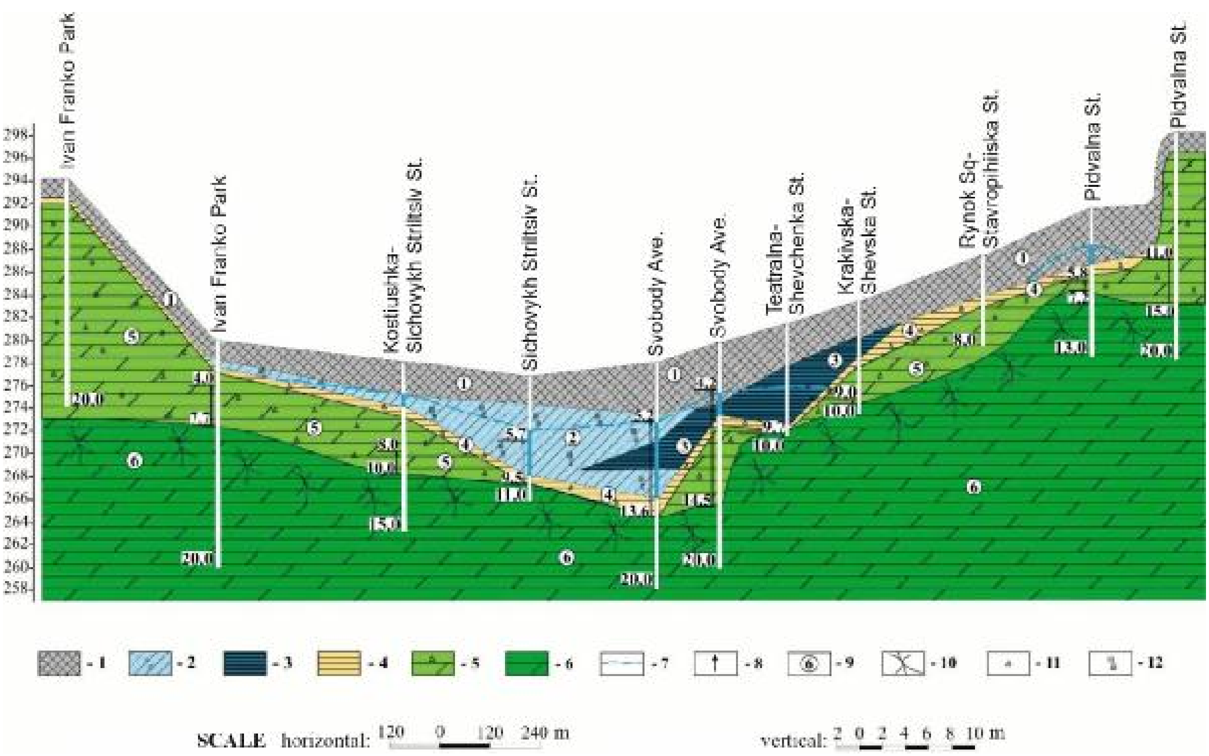

Fig. 4. Geological cross-section through the valley of the Poltva along the I-I line:

1 – technogenic soil; 2 – sandy loams, loams, peat clays, peats; 3 – fine sand; 4 – semi-hard marl clay; 5 – colmatation zone of marls; 6 – fissured marls; 7 – mirror of groundwater and technogenic waters; 8 – the pressure of artesian waters; 9 – layer number; 10 – cracks; 11 – marl fragments; 12 – pea).

Complete saturation of soils with water is typically observed at an average depth of 2.5 to 3.0 meters below the Earth’s surface. There is a sharp increase in organic matter content from this depth.

Calculations of the degree of pore filling showed that up to a depth of 2.5–3.0 m, it varies from 0.37 to 0.77, and below this mark, it typically exceeds 0.80. That is, from this depth, the pore space is filled with water, and the destruction of organic matter is practically excluded. However, in areas of prolonged natural or anthropogenic drainage, these processes can extend to deeper horizons.

The lithology of rocks and the presence of finely dispersed components play a crucial role in the processes that lead to the breakdown of organic matter. These finely dispersed components, due to their ability to attract and hold moisture, can significantly influence the moisture retention in soils. Under certain hydrodynamic conditions, this can lead to mechanical suffosion and self-compaction of soils. Developing these processes is a decisive factor in forming a bearing capacity deficit of the foundation of engineering structures and often leads to their deformation.

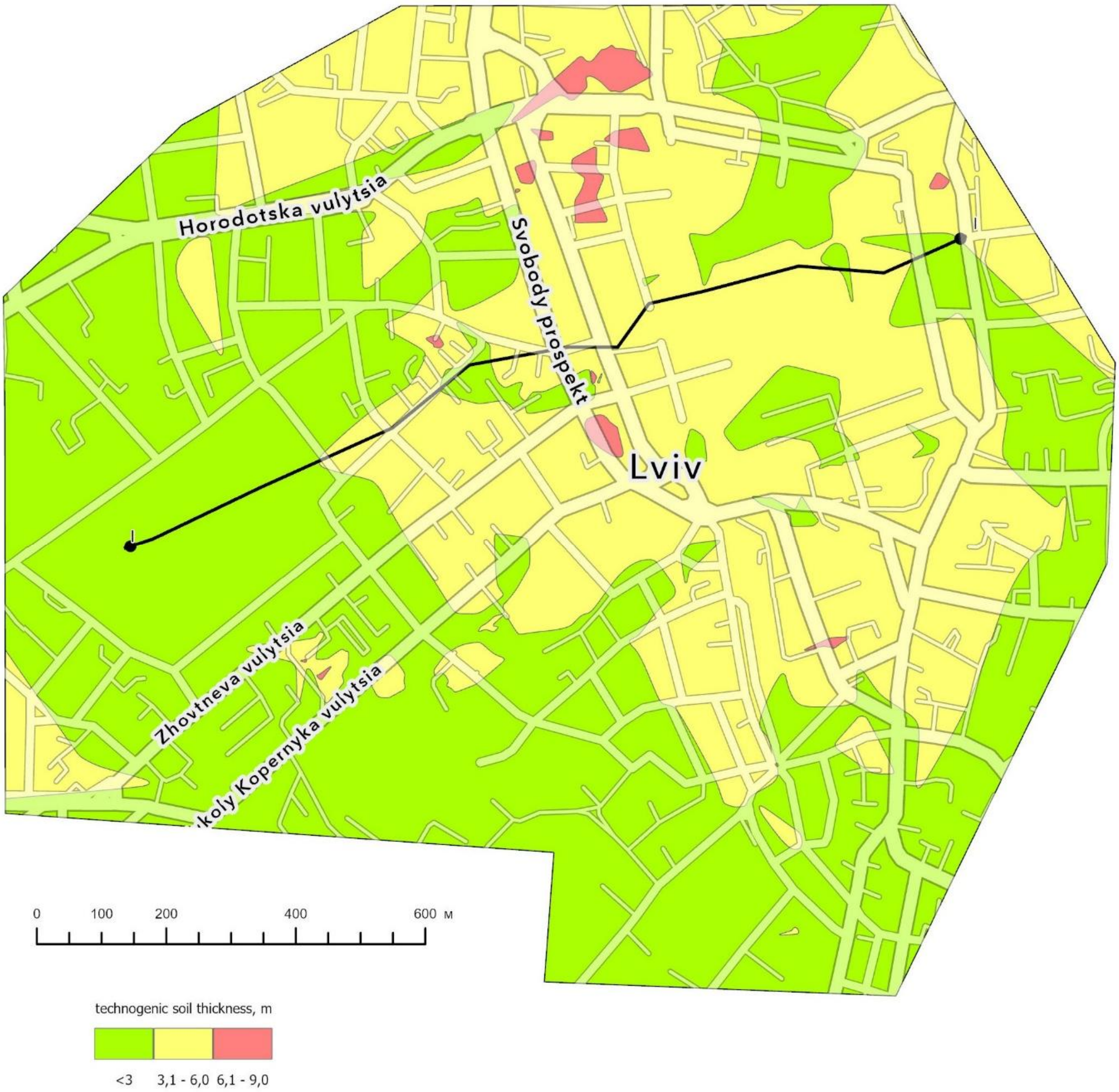

Fig. 5. Map of distribution and thickness of technogenic soils.

Significant fluctuations in the content of fractions of different sizes have caused a wide range of lithological variations in soils. Sandy loams, loams, clays, sands, coarse fragmentary, and organo-mineral soils are recorded in numerous sections. Most often, loams of varying degrees of peat content are found.

The natural moisture content of soils varies from 9 % to 380 % and is primarily controlled by the amount of organic matter present. It also determines a critical indicator of density, which ranges from 0.94 to 1.06 g/cm³ for fossil manure and sawdust, and from 1.34 to 2.10 g/cm³ for sandy-clay soils.

An equal range of vibrations characterises indicators of mechanical properties. The angle of internal friction varies from 2° to 35°, and the specific adhesion from 0.001 to 0.056 MPa. On this basis, soils are mainly of low strength. According to the magnitude of the modules of total deformation, which in most cases does not exceed 5.0 MPa, they should be considered weak.

The interval of its changes reaches two orders of magnitude (0.01−1.0 m/day). The upper part of the thickness of technogenic soils (up to 3 m), with a low content of organic matter, is characterised by medium corrosive activity to the material of building structures. At a depth of more than 3 m, high corrosive activity to the material of building structures is observed.

It should also be noted that technogenic soils are seismically unstable (IV category in terms of seismic properties) [State Building Standards (DBN), 2014].

The research has shown that the technogenic soils of the historical buildings of Lviv are a unique natural and anthropogenic formation with a complex internal structure, variegated lithological, petrographic, and chemical composition, and low physical, mechanical, and seismic properties. Pronounced sensory properties characterise these soils due to the presence in their material composition of several ephemeral elements (macro- and microorganic substances, easily soluble salts, etc.), which are very sensitive to changes in the air and humidity regime of the soil. The high heterogeneity of lithological composition, along with the presence of different-sized cavities formed by the decomposition of organic matter, creates favourable prerequisites for the development of mechanical suffosion and dewatering compaction processes. This variability requires mandatory consideration in the design and construction of underground structures.

Within the alluvial complex, different types of deposits are identified based on the conditions of accumulation and lithological composition. These include channel, floodplain, and old (swamp) deposits [Voloshyn, Pavlun, 2019].

Channel alluvium is represented by fine- to medium-grained and dusty sands, sometimes with lenses and layers of gravel and pebble material. Sediments of this genesis are distributed mainly in the right-bank part of the valley of the river Poltva. On its left bank, they are fixed only in the form of small spots. The average thickness of the layer is 3.5 to 6.5 m. Sands are characterised by high strength and deformation properties. The angle of internal friction is 33° on average, the specific adhesion is 0.005 MPa, and the filtration coefficient is 5.1 m/day. Below the groundwater level, they are characterised by buoyant properties.

The floodplain alluvium is composed of bluish-grey, thixotropic sandy loam and loam with layers and lenses of fine sand, sometimes with impurities of organic matter. The thickness of the layer of rocks of this type ranges from 1 to 3 m. Loams are primarily characterized by a stiff plastic consistency, although they can occasionally exhibit a soft plastic consistency as well. They exhibit relatively high strength properties, with an average internal friction angle of 23°, a specific adhesion of 0.023 MPa, and a relatively low modulus of deformation of 8 MPa.

Deposits of old alluvium occupy more than a third of the basin. They are concentrated mainly on the left bank of the river Poltva, as well as on the bottoms of the valleys of its tributaries. Lithologically, they are represented by peat loams, clays, and peats. Peat lies in separate lenses with a thickness ranging from 0.2 to 1.0–2.4 m. Most of them are located on Svoboda Ave., Bankivska str., Ivan Franko str., and Kovzhuna str. Peat rocks, in the form of a chain of isolated massifs, stretch along the left bank of the Poltva River. The largest layers in terms of thickness (6–12 m) were found near Mickiewicz Square, Hnatiuk Street, on the site of the Opera Theatre. The unification of various soil nomenclature types into a single layer is attributed to two main factors. First, they share a common characteristic: a high organic substance content, which can be as much as 50 %. Second, there are complex spatial relationships, including facies substitution, layering, and lenticular occurrences that can be observed even within individual structures.

The natural moisture content of these soils varies from 17−30 % to 106−324 %, and the content of organic substances in some areas reaches 90 %. The turnover rate ranges from 0.3 to 1.29. Peat is predominantly medium-decomposed. Their density in its natural state ranges from 0.80 to 1.73 g/cm^3. The angle of internal friction varies from 1° to 7° under different vertical loads, and the specific adhesion ranges from 0.025 to 0.073 MPa. The modulus of strain is very low. In the range of vertical loads of 0.2−0.3 MPa, it is, on average, 1.7 MPa. The content of organic matter in them significantly influences the physical and mechanical properties of peaty soils. With an increase in its content and the degree of decomposition of peats, the strength and deformation properties are significantly reduced.

From the above, rocks of this genetic type, due to the high organic matter content, are characterised by low mechanical properties and high sensitivity to anthropogenic influences, particularly dewatering and vibration. When constructing deep pits, it is necessary to employ specialised construction methods and complex techniques to ensure the stability of the slope walls and protection against dewatering.

Deluvial accumulations are composed of sandy loams of loess appearance, rigid and plastic consistency, sandy with layers of sand, which cover the slopes of Mount Citadel in a thick layer (from 1−3 to 10 m). They are dense, characterised by high mechanical properties, and lie above the groundwater level. In particular, the natural moisture content of sandy loams varies from 9 % to 24 %, and the density of natural soil ranges from 1.80 to 2.03 g/cm^3. The average value of the angle of internal friction is 29°, the specific adhesion is 0.009 MPa, and the deformation modulus is 16 MPa.

Neogene deposits with stratigraphic inconsistencies lie on the eroded surface of Upper Cretaceous marls and the weathered crustr. They are composed of low-moisture, fine quartz sands with layers of sandstone. They lie above the groundwater level in small massifs on the slopes of Svyatoyurska, Zamkova, and Citadel. Sands are characterised by medium density and are less often dense. The angle of internal friction is 36° on average, the specific adhesion is 0.003 MPa, and the modulus of deformation is 20 MPa. At the same time, the occurrence of the sand column in the aeration zone and the presence of layers of medium-grained and dusty sand within it are favourable for the development of mechanical suffosion.

The deposits of the Upper Cretaceous belong to the Maastrichtian layer (Lviv Formation) and are represented by the so-called Lviv marls. The Upper Cretaceous deposits are distributed throughout the city. The depth of their occurrence closely correlates with relief. On the slopes of the basin, they are located at depths of 1.5–3.0 m in the areas of the most significant erosion cuts in the valley of the River Poltva, at depths ranging from 6 to 15 m. The degree of cracking within a 50-meter thickness varies significantly in plan and depth. Uniaxial compression resistance varies from 0.3 to 1.0 MPa to 15.0 MPa. The filtration coefficient ranges from 3.3–6.3 m to 10.0 m/day. Marls are highly sensitive to weathering agents, which cause them to quickly loosen and lose their load-bearing capacity. Over time, marls are gradually replaced by clayey eluvium, consisting of hard and semi-hard carbonate loams and clays located in the uppermost, most weathered layer.

These clays are dense and contain fragments of marl, with the proportion of marl increasing at greater depths. Characteristically, clays exhibit high strength indicators: the angle of internal friction is 28°, adhesion is 0.037 MPa, and the modulus of deformation is 25 MPa. Due to their high clay content, these soils are nearly impervious to water. The thickness of the clay layer varies from 0.5 to 4.0 m. Under the clay layer is a layer of varying thicknesses, known as the "colmatation zone", composed of marls. Due to the practical waterproofness of clays and marls of the colmatation zone, artesian groundwater is formed, and its pressure is ensured. On the other hand, natural or technogenic aquifers accumulate on their roof in places close to the surface of clays.

Groundwater. Two aquifers were discovered in the central part of Lviv: Quaternary and Upper Cretaceous [Voloshyn, 2010]. The first layer from the surface is the aquifer of Quaternary sediments, which was formed on the water-resistant eluvium of Upper Cretaceous marls.

Water-containing rocks comprise a complex of alluvial deposits from the River Poltva, varying in lithological composition, and, less frequently, deluvial accumulations. The waters of the horizon are non-pressure. They lie at depths from 2–4 m to 10.5 m. In some areas, local domes and depressions of levels with an amplitude of 1.5–2.5 m, caused by anthropogenic factors, are recorded. Only in areas of artificial drainage (Opera and Ballet theatre, Mytna Square, and on the slopes of Citadel Mountain), the depths of occurrence exceed 6–9 m. In the peripheral parts of the Poltva River valley, the deposits are anhydrous.

The thickness of the aquifer varies from 0.5–3.0 m to 8.0 m. In most cases, it does not exceed 2–5 m. The aquifer is fed by the infiltration of atmospheric precipitation, partial discharge of water from the Upper Cretaceous aquifer, and leaks from engineering networks. Waters are characterised by medium and weak general acidity, carbon dioxide, and sulphate aggressiveness to the concrete of reinforced concrete structures.

The second from the surface is the horizon of Upper Cretaceous artesian waters associated with fissured marls of the Maastrichtian layer. The depth of the hydrostatic water level of this horizon varies from 2.8 m on Bankova str. to 11.6 m on M. Kryvonosa str.

The amount of pressure also fluctuates widely. In the area of the Puppet Theatre, the water pressure is non-existent, and in the wells on Svoboda Avenue, the pressure ranges from 9.5 to 10.3 m. The thickness of the waterproof soil layer ("colmatation zone"), which provides pressure, varies widely from 1.0 to 8.0 m. On the slopes of the valley, there are also areas with different depths of the aquifer roof, the thickness of the overlapping layer, and pressure. Moreover, even in small areas, these parameters can vary significantly, creating water threats during underground construction.

Quaternary and Upper Cretaceous aquifers are hydraulically interconnected. That is, when technogenic depressions are created in the Upper Cretaceous aquifer, or a significant decrease in its pressure, there is a real threat of lowering the level of the Quaternary horizon, which is accompanied by dewatering of organic and organic-mineral soils and their compaction. The filtration coefficients of water-containing soils vary from 0.01 to 5.1 m/day.

Geological processes. Endogenous and exogenous processes develop in the study area [Voloshyn, 2001, 2004]. According to [State Building Standards (DBN), 2014], the territory of Lviv is seismically hazardous, with background seismicity of 6 points. Its central part is composed of seismically unstable soils (technogenic soils, rocks of old facies, and saturated sands). They can increase the background seismicity of the site by up to 7 and even 8 points. Surfaces are localised in space. Damaging events are primarily recorded in the riparian area of the canalised Poltva River valley. Positive deformations are found in its domesticated regions and on the slopes of the depression. Multipolar deformations recorded in the central part of Lviv may indicate their polygenetic nature. Displacement of the Earth's surface with a positive sign (uplift) is primarily associated with the development of modern tectonic movements. In contrast, adverse displacement (subsidence) is caused by both natural factors (such as the presence of weak soils, peat, etc.) and technogenic factors. Deformations of the Earth's surface, especially negative ones, with absolute values in some areas exceeding 354 mm over the last period, are a critical risk-forming factor and should be considered during underground construction.

The most common exogenous process is mechanical suffocation and flooding [Voloshyn, 2004]. The focus of the development of suffosion processes is confined to the valley of the River Poltva, its tides, and defensive ditches, which are "covered" with a powerful thickness of soils from the cultural layer. The risk of suffosion primarily occurs in areas where water supply and sewage systems do not function properly. This risk is less prevalent on developed slopes composed of Neogene sands located in the aeration zone, such as the northern slopes of the Lviv Plateau and the southeastern slopes of the Roztochchia uplands.

The development of suffosion processes is primarily accompanied by the formation of failure funnels with diameters ranging from 1−3 m to 5−7 m and depths of 2−3 m, significantly affecting the stability and operational suitability of engineering structures. The intensity of sinkhole formation is very high. In some years, it exceeds several dozen forms per 1 km^2.

Technogenic flooding is widespread in the central part of the city. The main factors of flooding in the territory of the historical buildings of Lviv include:

− close to the surface (3–6 m) occurrence of water-resistant marl clays;
− elimination of natural drains (Poltva, Belaya, Ortysh stream) and artificial drains (defensive ditches), backfilling of numerous springs;
− formation of a powerful thickness (6–9 m) of technogenic soils (cultural layer);
− the presence in the soil layer of numerous structures that create a barrage effect;
− significant losses of water from water pipelines (more than 1.2 thousand m^3 per day per 1 km^2) and sewerage networks.

Flooding manifests itself in the form of a significant number of isolated technogenic water domes located on the slopes of the Poltva basin, where there is no natural water, and a continuous aquifer within the floodplain terrace of the Poltva River. The total area of the flooded regions exceeds 47 hectares, which is 23.4 % of the total area of the studied area.

The depth of the technogenic aquifer varies, ranging from 1.2–2.0 m to 3.5 m. The content of water-soluble salts in them ranges from 5.0 to 8.0 g/l and even up to 13.6 g/l. The development of technogenic flooding processes significantly affects the ecological state of the urban environment due to:

− changes in the state, physical, mechanical, and corrosive properties of soils, which lead to the loss of stability of architectural monuments located here;
− salinisation and destruction of building structures buried in the soil;
− flooding of basements of residential buildings;
− pollution of groundwater;
− increased seismic vulnerability of the territory.

Scientific novelty

Various types of risk factors associated with underground construction in the central part of Lviv have been identified and studied. These include: geological factors that encompass the structure of the rock mass, its composition, condition, and the physical, mechanical, and seismic properties of the rocks. It also considers the rocks' vulnerability to external influences; hydrogeological factors, including the number of aquifers, the depth of groundwater, their chemical composition, aggressiveness towards building structures, pressure, and the relationships between aquifers; geodynamic factors, involving the speed of current tectonic movements, the development of suffosion processes, deformations of the Earth's surface, and the risk of flooding.

By examining these factors, we can gain a more comprehensive understanding of the risks associated with underground construction. For the first time, the geological risks associated with underground construction in various areas of the study region have been assessed. To gather reliable information for developing a project to establish subterranean spaces in the central part of Lviv, it is essential to continue monitoring the dynamics of the Quaternary and Upper Cretaceous aquifers.

Practical significance

The results will enable us to ensure the rational spatial location of underground parking lots and other underground urbanisation objects. We will select effective construction technologies that minimise risks to the stability of the designed structures, adjacent buildings, and engineering infrastructure facilities. They will also serve as a basis for predicting the long-term negative consequences of constructing and operating underground structures.

Conclusions

The analysis of the geological structure, composition, and properties of rocks, as well as hydrogeological conditions, revealed that the central part of the city exhibits a varying degree of geological risk associated with underground space development.

The slopes of the Poltva valley and its right-sided structural terrace, composed of waterless technogenic, Quaternary deluvial, and Neogene deposits, are characterised by the most favourable conditions and low geological risk for underground urbanisation. Groundwater in the marls of the Upper Cretaceous lies here at a depth of more than 10−15 m below their roof.

Less favourable conditions are characterized by areas that are conditionally favourable and have medium geological risk. These locations are in contact with floodplains or are partially floodplain areas, where organo-mineral soils are either absent or very thin. They are covered with Upper Cretaceous marls and lie above the groundwater level. The main risk factor in these areas is the shallow depth of the roof of the chalk aquifer, along with the significant pressure it experiences, particularly near the monument to Ivan Franko. The hydrogeological conditions in this region create the potential for groundwater to break through into deep pits, which necessitates a substantial reduction in the level of the chalk aquifer. If this does not occur, it may result in deformations of the Quaternary horizon, as well as dewatering and compaction (subsidence) of organo-mineral soils.

The most unfavourable areas for the construction of underground structures (with the highest geological risk) include those on the left-sided floodplain terrace, close to the bed of the Poltva River. They are characterised by a thickness of up to 8−12 m of soils unfavourable for construction (peat, weak peat, technogenic, quicksand, etc.). A powerful (4−8 m) quaternary aquifer is widespread within its boundaries. Even minor changes in its dynamic regime (decrease) can trigger significant dewatering, compaction, and consolidation processes. These processes can result in subsidence and threaten the destruction of underground structures and above-ground buildings within the sphere of influence of underground construction. This situation also endangers the population.

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ПРОГНОЗНА ОЦІНКА ВПЛИВУ НЕБЕЗПЕЧНИХ ГЕОДИНАМІЧНИХ ПРОЦЕСІВ НА ПІДЗЕМНЕ БУДІВНИЦТВО В ЦЕНТРАЛЬНІЙ ЧАСТИНІ ЛЬВОВА

Метою досліджень є прогнозна оцінка впливу на підземне будівництво в центральній частині Львова небезпечних геодинамічних процесів, пов’язаних з особливостями геологічної будови, гідрогеологічних умов, специфічними властивостями гірських порід та хімічним складом підземних вод. Актуальність роботи. У місті Львові, як і у багатьох великих містах України, надзвичайно гострими є проблеми транспорту і паркування автомобілів. Особливо актуальні вони для центральної частини міста, яка характеризується густою мережею вузьких вулиць, надзвичайною насиченістю автотранспортом, щільною забудовою, великою кількістю транспортопритягальних об’єктів. Для вирішення цієї складної проблеми місцева влада планує будівництво низки підземних багаторівневих паркінгів. Їхнє проєктування та будівництво потребують детальної інформації про будову, склад, властивості геологічного середовища та оцінку геологічних ризиків, пов’язаних з будівництвом та експлуатацією таких споруд. Методика досліджень. Зібрано та комплексно проаналізовано інформацію про геологічні умови, склад, фізико-механічні, фільтраційні й корозійні властивості ґрунтів, агресивність підземних вод, конструктивні особливості споруд, типи їхніх фундаментів, досвід будівництва підземного трамваю. Спеціально пробурено понад 50 дослідних свердловин, виконано геофізичні, інженерно-геодезичні та лабораторні дослідження, побудовано комп’ютерні картографічні моделі геологічного середовища. Результати. На основі отриманих даних схарактеризовано геологічну будову, гідрогеологічні умови, фізико-механічні, сейсмічні властивості грунтів та морфодинамічні процеси у центральній частині міста. Виконано просторовий аналіз ризикоформувальних складових геологічного середовища та оцінено ризики його будівельного освоєння. Наукова новизна. Виявлено різні типи ризикоформувальних чинників для підземного будівництва в центральній частині Львова: геологічних (будова породного масиву, склад, стан, фізико-механічні та сейсмічні властивості порід, їхня вразливість до зовнішнього впливу), гідрогеологічних (кількість водоносних горизонтів, глибина залягання підземних вод, їхній хімічний склад і агресивність до будівельних конструкцій, напір, взаємозв’язок між водоносними горизонтами тощо), а також морфодинамічних (швидкість сучасних тектонічних рухів, розвиток суфозійних процесів та деформацій земної поверхні). Вперше надано прогнозну оцінку геологічних ризиків під час підземного будівництва на різних ділянках досліджуваної території. Практична значущість. Одержані результати дадуть можливість забезпечити раціональне просторове розташування підземних паркінгів та інших об’єктів підземної урбанізації, вибрати ефективні технології будівництва, які забезпечують мінімальні ризики для стійкості проєктованих споруд та прилеглих до них будівель і об’єктів інженерної інфраструктури, а також будуть слугувати інформаційною базою для прогнозування віддалених у часі негативних наслідків будівництва та експлуатації підземних споруд.

Ключові слова: підземна урбаністика, рельєф, техногенні ґрунти, органічні ґрунти, пливуни, підземні води, фізико-механічні та сейсмічні властивості ґрунтів, геологічні ризики, небезпечні геодинамічні процеси.

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