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Article

Stratigraphic-genetic complexes of the bedrock of Lviv city and their geotechnical properties

Stratigrafsko-genetski kompleksi kamninske podlage mesta Lviv in njihove geotehnične lastnosti

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Ključne besede: stratigrafija, genetski kompleksi, facies, geotehnične lastnosti, tla, Lviv

Abstract

The geological basis of engineering geological surveys is based on age and genetic factors. The age is determined by the regional stratigraphic scheme. Identification of specific features and criteria of genetic subdivisions of rocks is the main task of studying the geological structure of the territory of Lviv city for geotechnical purposes. Stratigraphic and genetic complexes should be identified for this purpose based on the stratigraphic-genetic scheme of bedrock dissection. The bedrock of the Cretaceous and Neogene systems was separated into independent stratigraphic-genetic complexes by this principle and dissected into engineering-geological elements based on the application of stratigraphic and geotechnical research methods. The article describes each engineering-geological element with characteristic geotechnical properties and concludes their use as a basis for foundations of buildings and structures. The soils that are the most difficult in geotechnical terms are also analyzed, recommendations on foundation construction on problematic soils are given, and a set of engineering preparation measures aimed at improving the general engineering-geological situation in Lviv city are defined.

Izvleček

Geološka podlaga inženirsko-geoloških raziskav temelji na starosti in genetskih dejavnikih. Starost se določa z regionalno stratigrafsko shemo. Opredelitev specifičnih značilnosti in meril genetske delitve kamnin je glavna naloga pri preučevanju geološke zgradbe območja mesta Lviv za geotehnične namene. V ta namen je treba, na podlagi stratigrafsko-genetske sheme razčlenitve kamnin, opredeliti stratigrafske in genetske komplekse. Kamnine krednega in neogenskega sistema so bile po tem načelu razdeljene na samostojne stratigrafsko-genetske komplekse in razčlenjene na inženirsko-geološke elemente na podlagi uporabe stratigrafskih in geotehničnih raziskovalnih metod. Članek opisuje vsak inženirsko-geološki element z značilnimi geotehničnimi lastnostmi ter podaja zaključke o njihovi uporabi kot osnovi za temeljenje stavb in objektov. Analizirana so tudi tla, ki so v geotehničnem smislu najzahtevnejša, podana so priporočila glede gradnje temeljev na problematičnih tleh in opredeljen je nabor inženirskih pripravljalnih ukrepov, namenjenih izboljšanju splošnega inženirsko-geološkega stanja v mestu Lviv.

Introduction

Lviv is one of the most dynamically developing cities in Ukraine in terms of construction, in connection with which there is a need for a detailed study of the geotechnical properties of soils as the basis for the foundations of buildings and structures.

The territory of Lviv city is geostructurally located within the Lviv Paleozoic Trough, corresponding to a deeply submerged section of the crystalline basement of the southwestern margin of the East European Platform. Paleozoic, Mesozoic, and Cenozoic rocks take part in the geological structure of the area. Of the extensive rock complexes developed within the study area, three different-aged and different-genesis rock complexes are of decisive importance for prospective construction: Upper Cretaceous, Neogene and Quaternary. We will focus on the description of the bedrock Upper Cretaceous and Neogene rocks in this paper and their geotechnical properties.

Geotechnical characterization of soils is based on the identification and mapping of stratigraphic-genetic complexes of rocks, accordingly, the geological basis of engineering-geological surveys should be based on two factors – age (stratigraphic) and genetic. If the age factor with sufficient completeness to fulfill the tasks is strictly regulated by regional stratigraphic schemes adopted by the Interdepartmental Stratigraphic Committee, there is no accepted scheme for the genetic division of rocks. The main task of studying the geological structure of Lviv city from the point of view of geotechnical use and development of the territory was to identify specific features and criteria of the genetic division of rocks corresponding to the specialization of works.

This article presents the results and bases of the adopted stratigraphic-genetic scheme of bedrock dissection, necessary for the allocation of stratigraphic-genetic complexes of the territory of Lviv city. Therefore, this scheme, especially in its genetic part, cannot have regional significance but is only adapted to a specific area according to the intended purpose of the works (Gruzman, 1980).

Study area

Lviv is located in the central part of the Lviv Region between Yavoriv, Zhovkva and Pustomyty Districts, in the Eastern European time zone at the 24^{th} meridian. The city is located approximately 540 km west of Kyiv, at a distance of about 70 km from the border with Poland (Fig. 1).

Bedrocks are confined to certain geomorphological units, so it makes sense to briefly present the geomorphological zoning of the territory of Lviv city. It is also necessary to designate individual landforms that will be encountered in the text of this article. Lviv city belongs to the Volhynian-Podolian Region of strata-denudation upland by the map of geomorphological zoning. The territory of the Lviv city is located within two geomorphological subregions – the Podolian structural-denudation upland on Cretaceous and Neogene deposits and the Lower Polissia strata-accumulative plain on Cretaceous deposits. Geomorphological subregions are further divided into districts and subdistricts (Gruzman, 1980) (Figs. 2, 3).

Fig. 1. Administrative location of the Lviv city.

COUNTRY	REGION	SUBREGIONS	DISTRICTS	SUBDISTRICTS		
				NAME OF SUBDISTRICTS		CHARACTERISTIC OF SUBDISTRICTS
EASTERN EUROPEAN POLYGENIC PLAIN	VOLHYNIAN-PODOLIAN REGION OF STRATO-DENUDATION UPLAND	A. PODOLIAN STRUCTURAL-DENUDATION UPLAND	I. LVIV PLATEAU	I_1	LVIV PLATEAU	GENTLY-DELUVIAL, GENTLY-WAVOUS, WEAKLY DISSECTED
				I_2	LVIV-BOBYRSK HILLY UPLAND	STRUCTURAL-EROSIONAL, STRONGLY DISSECTED EASTERN PART OF LVIV PLATEAU
				I_3	DISSECTED NORTHERN SLOPE PART OF LVIV PLATEAU	EROSIONAL CAPE PROTRUSIONS OF LVIV PLATEAU, THAT BEND AROUND POLTVA VALLEY
			II. ZUBRA VALLEY	II_1	BOTTOM OF ZUBRA VALLEY	ALLUVIAL FLAT AND CANOPY CONCAVE CHANNEL AND FLOODPLAIN SURFACES OF ZUBRA VALLEY
				II_2	SLOPES OF ZUBRA VALLEY	EROSIONAL-DELUVIAL, GENTLE
			III. HILLY RIDGE ROZTOCZE	III_1	HILLY RIDGE ROZTOCZE	HIGHLY EROSIONAL, HILLY RIDGE UPLANDS
				III_2	SOUTHERN-WESTERN SPURS OF HILLY RIDGE ROZTOCZE	AEOLIAN-DELUVIAL, GENTLY-WAVED AND SMALL-RIDGY, GENTLY-DISSECTED
				III_3	RESIDUAL HIGHS	STRUCTURAL-DENUDATION, OUTLIER, GENTLY-SUMMIT, TERRACED HILLS AND UPLANDS
			IV. BILOHIRIA-MALCHYTSKA VALLEY	IV_1	BILOHIRIA STRUCTURAL BASIN	ACCUMULATIVE, FLAT BOTTOM WITH GENTLY SLOPES, SWAMPED (BILOHIRIA STREAM VALLEY)
				IV_2	RYASNA VALLEY	ACCUMULATIVE, FLAT BOTTOM WITH GENTLY SLOPES, HEAVILY SWAMPED
		B. LOWER POLISSIA STRATIFIED-ACCUMULATIVE PLAIN	V. POLTVA VALLEY	V_1	FLOODED TERRACED SURFACES OF POLTVA RIVER	ACCUMULATIVE, FLAT
				V_2	UNDERFLOODED TERRACED SURFACES OF POLTVA RIVER	
			VI. UPLANDS OF RIDING LANDS OF BUH	VI	VYNNYKY RIDGE	EROSIONAL RIDGE WITH GENTLY SLOPES AND RIDGY CRESTS

Fig. 2. Scheme of geomorphological zoning of Lviv city.

Materials and methods

The basis for the genetic dissection of rocks was the available facies-ecological studies of the Paleogene and Neogene of Lviv city (Kudrin, 1966) and the experience of large-scale (1:50 000) geological survey. To describe the stratigraphic-genetic complexes of Lviv city's bedrock deposits we used the works on the stratigraphy of the loess formation of Ukraine (Veklych, 1968), stratotypes and biostratigraphy of Miocene deposits of the Volhynian-Podolian plate (Venglinsky & Horetsky, 1979), stratigraphy of the Tortonian deposits of Volhynia-Podolia (Vyalov & Horetsky, 1965), Stratigraphic Code of Ukraine (Hozhyk, 2012), stratigraphic schemes and legends for the Carpathian region (Biryuleva et al., 1972), geological atlas of Lviv city and its surroundings (Lomnicki, 1897), stratigraphy of the Middle Miocene deposits of Opillia (Kazakova, 1952).

As for geotechnical studies of the territory of Lviv city, the existing information is based on the materials of reports on engineering-geological surveys for residential-civil and industrial objects. 357 geotechnical reports were analyzed, and those materials were collected and systematized

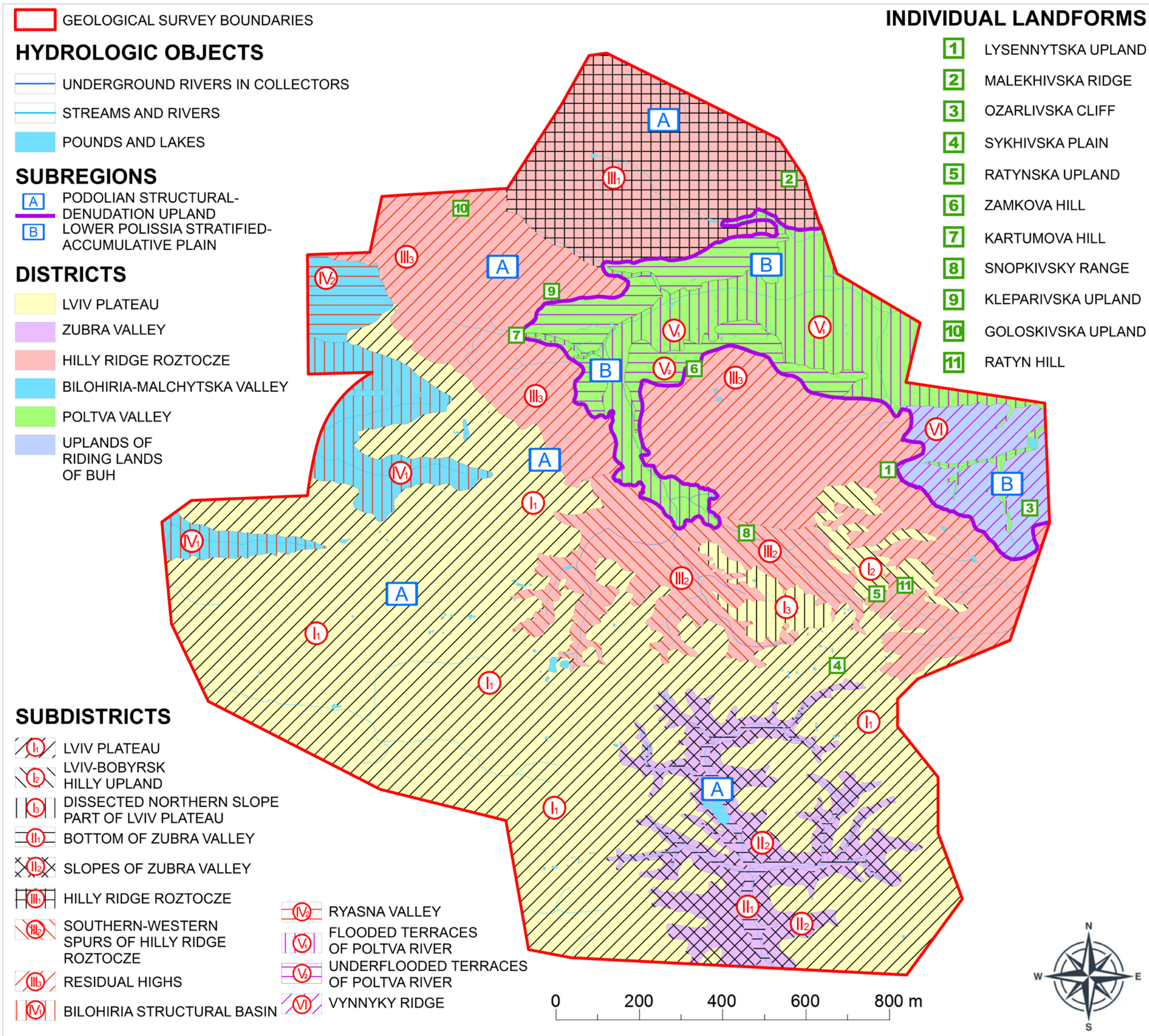

Fig. 3. Geomorphological zoning and individual landforms of Lviv city.

at the Lviv Branch of the "Ukrainian Institute of Engineering Technical Exploration for Construction" (SE "LF UKRIINTR"). Also the main ideas on engineering-geological assessment of stratigraphic-genetic complexes were taken from several scientific works of Ukrainian (Mokritskaya, 2012, 2019; Budkin & Cherkez, 2000) and foreign scientists (Hataullin, 1991; Kopylov & Melchakova, 2020; Arkhipov et al., 1980; Slavinskaya & Lyubimova, 2008; Bogomolov, 2011).

Lithological, paleontological and chronostratigraphic research methods were applied in the study of the stratigraphy of the bedrock of Lviv city. The group of lithological methods included dissection and correlation based on visual features (establishing sediment types, colour, density, strength, structure, texture, presence of inclusions, secondary alteration, signs of cyclicity, etc.). Mineralogical-petrographic methods included microscopic diagnosis of the minerals that make up the rocks and structural analysis using X-rays.

The paleontological method was used to determine the relative ages, stratigraphic separations and correlations of sedimentary rocks based on the sequence of fossil assemblages contained within them, as a result of biological evolution and changes in environmental conditions. For the paleontological method the groups of organisms with high abundance, rapid evolution and wide distribution, whose remains are well preserved, in our case these were red algae and several shell cephalopod mollusks, were of greatest importance.

The use of chronostratigraphic methods solved the problem of comparing sections (private and composite) with the general stratigraphic scale and global correlation of sedimentary strata. The method is based on a comprehensive substantiation of the age of the lower strata boundary, linking it to the anchored "golden nail" tier boundary, and tracing this "isochronal boundary" within the basin and beyond based on a guiding correlation event (Zorina, 2015) (Fig.4).

Geotechnical research methods included borehole drilling and mining, field and laboratory studies of the soils (engineering-geological elements) identified within each stratigraphic-genetic complex. All strength and deformation characteristics of both rocks and soils were determined in the field. The compressibility of soils was studied by die methods, pressiometers, and dynamic and static probing.

To realize die loads in the borehole, boreholes with a diameter of more than 320 mm were drilled. Soil testing was carried out by special installations, which make it possible to work at a borehole depth of up to 20 m. A 600 cm^2 die was lowered to the bottom of the borehole. The load on the die was transmitted through a rod on which a platform with a load was placed. The modulus of deformation was determined by the formula.

Pressiometric studies were carried out in clayey soils using exploratory boreholes. The pressiometer is a rubber cylindrical chamber that is lowered into the borehole to a predetermined depth. The chamber is expanded by liquid or gas pressure. In the process, radial ground displacement and pressure are measured in the borehole walls. This makes it possible to determine the modulus of deformation of the soils.

Probing was used to study rock strata up to a depth of 15–20 m. The essence of the method was to determine the resistance to penetration of the probe into the ground. Probing gave an idea of the density and strength of soils at a certain depth and characterized changes in the vertical section.

The shear resistance of soils in the field was assessed in both rocks and soils. The shear resistance of soils was determined by the stress limits at which they begin to fracture.

In rocks, the experiments were carried out in construction pits, in which the pillars of undisturbed soil of columnar type are left. A horizontal shear force was applied to the pillars. At the same time, the experiments were carried out on at least three columnar pillars for the correct determination of internal friction and specific cohesion. Shifting in soils was performed in two ways: 1) on targets; 2) using rotary shears with impeller torsion. The operation on targets is similar to rocks. The impeller is a paddle device and is used to determine shear resistance in dusty clay soils. A four-bladed impeller probe was lowered into the borehole bottom, pressed into the soil and rotated. The torque was measured and the shear resistance was calculated (Ananyev & Potapov, 2005).

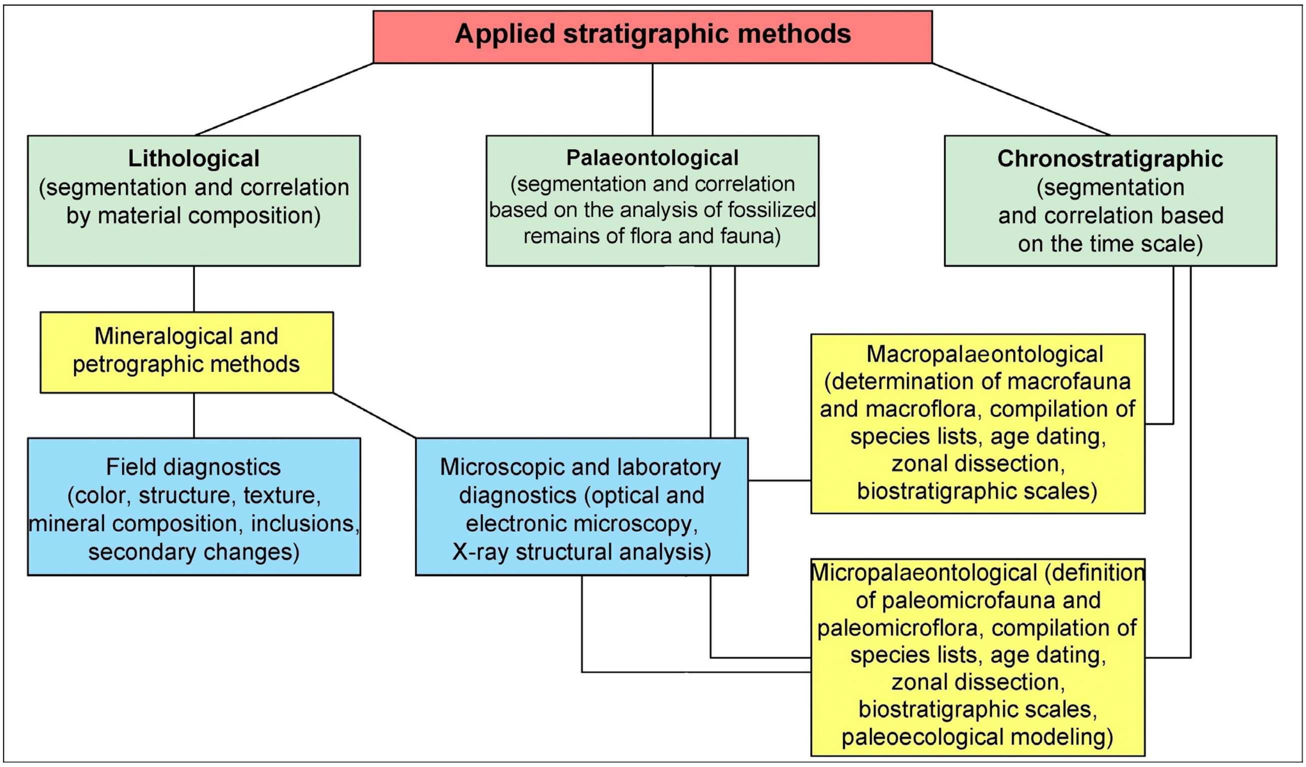

Fig. 4. Stratigraphic methods of the current study.

Laboratory soil testing is also an important geotechnical method. Soil samples for laboratory investigations were collected from soil layers in boreholes located at the construction sites under investigation. Soil samples were delivered to the laboratory as monoliths or loose samples.

All physical-mechanical and physical-chemical properties of soils can be determined in laboratory conditions. Each characteristic of these properties is defined according to its SSU, e.g. physical-mechanical, physical-chemical characteristics are defined according to SSU B V.2.1-3-96, particle size distribution is defined according to SSU ISO 11277:2005, tensile strength is defined according to SSU B V.2.1-4-96, etc. (Fig. 5).

Geotechnical research methods included borehole drilling and mining, field and laboratory studies of the soils (engineering-geological elements) identified within each stratigraphic-genetic complex. All strength and deformation characteristics of both rocks and soils were determined in the field. The compressibility of soils was studied by die methods, pressiometers, and dynamic and static probing. In-situ and laboratory investigations were performed using Ukrainian standards

Today laboratory tests remain the main type of determination of physical-mechanical and physical-chemical properties of soils. A number of characteristics, for example, natural moisture content, density of soil particles and some others are determined only in laboratory conditions and with high enough accuracy. The names and values of indicators of geotechnical properties of soils will be displayed further in the article in the relevant tables (Trofimov et al., 2005).

Results

The Upper Cretaceous complex (k_2m_2) developed within the city of Lviv is part of the so-called Lviv Cretaceous trough, composing the uppermost part of the Cretaceous rocks (Figs. 6, 7, 8). It is covered everywhere by Neogene and Quaternary deposits, exposed on the daytime surface only on the sides of deeply incised ravines in the southeast of the territory within the Lysennytska Upland. Cretaceous rocks reach the subquaternary surface in the areas of the Poltva River valley, where they form the bottom of the valley, and also form the bedrock base of the loess cover of the Vynnyky ridge and eastern spurs of hilly ridge Roztocze. Cretaceous rocks are lithologically represented by gray, light-gray, and greenish-gray marls, weakly sandy, weakly layered with interlayers of marly limestone, in some areas with a high content of sponge opicules, fragments of inoceramol shells and other detritus. The bulk of the rock under a microscope is composed of the finest silty particles of carbonate-clayey composition, their size does not exceed 0.01 mm, which determines its pelitomorphic structure. Structurally, the rock is characterized by the alternation of thin layers enriched to varying degrees in the detrital eleuritic component, which determines the eleuritic-pelitic structure and thin-layered texture of the rock. Clastic material (up to 17 %) whose grain size does not exceed 0.1 mm is represented mainly by quartz and glauconite, with minor amounts of feldspars, sericite, zircon, and rutile.

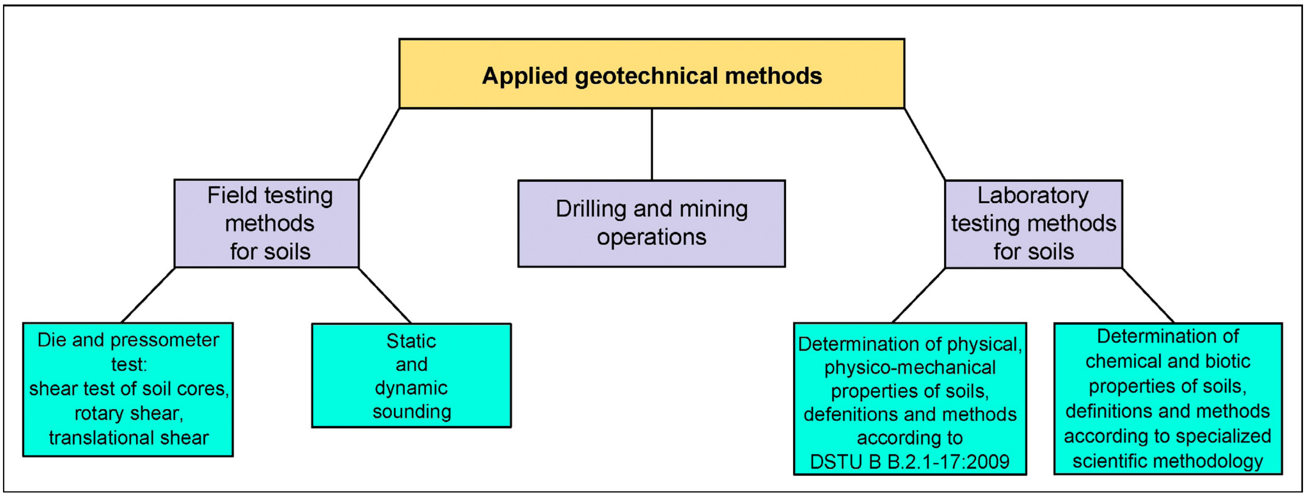

Fig. 5. Geotechnical methods of the current study.

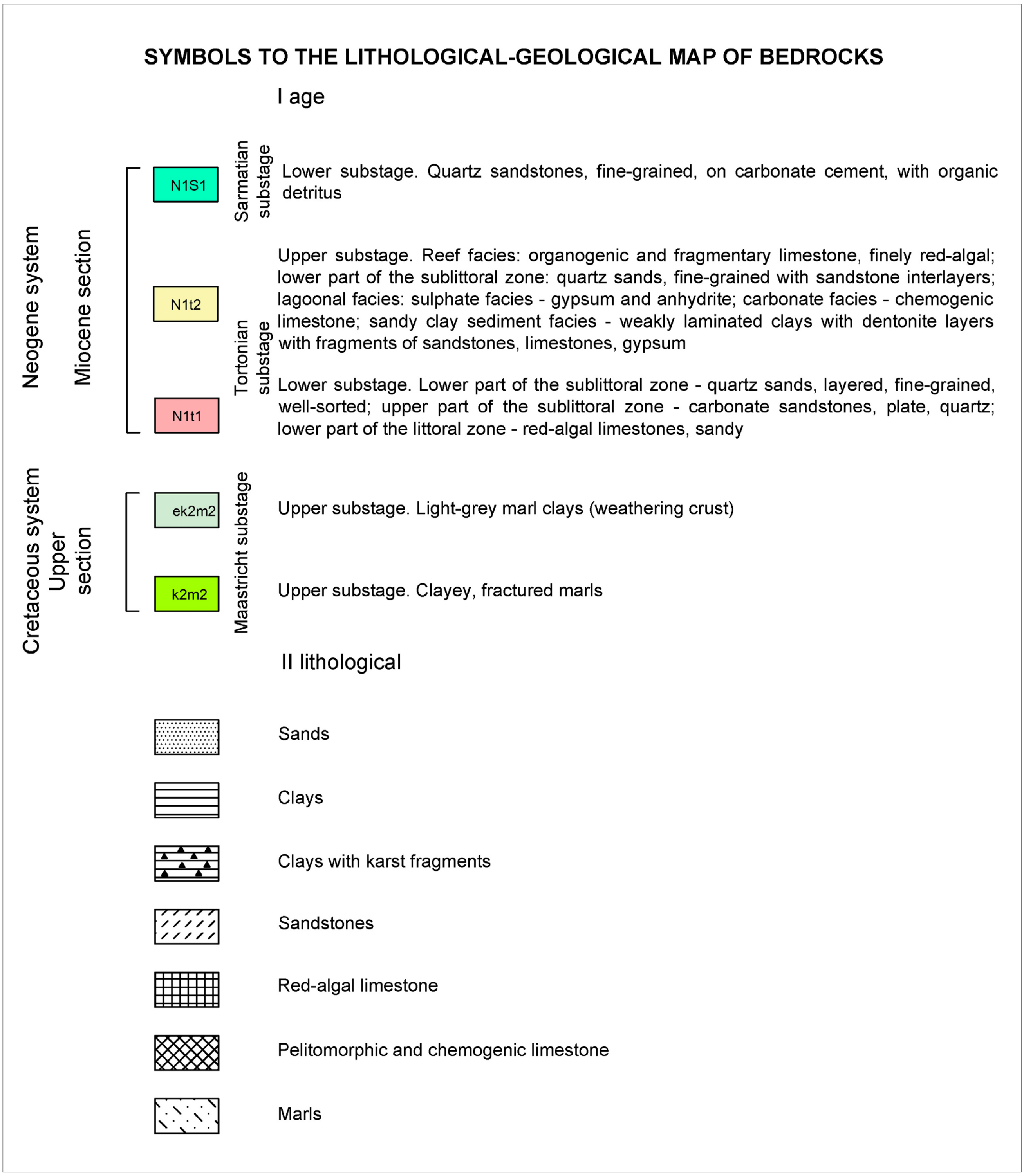

Fig. 6. Symbols for the lithological-geological map of the bedrock of Lviv city.

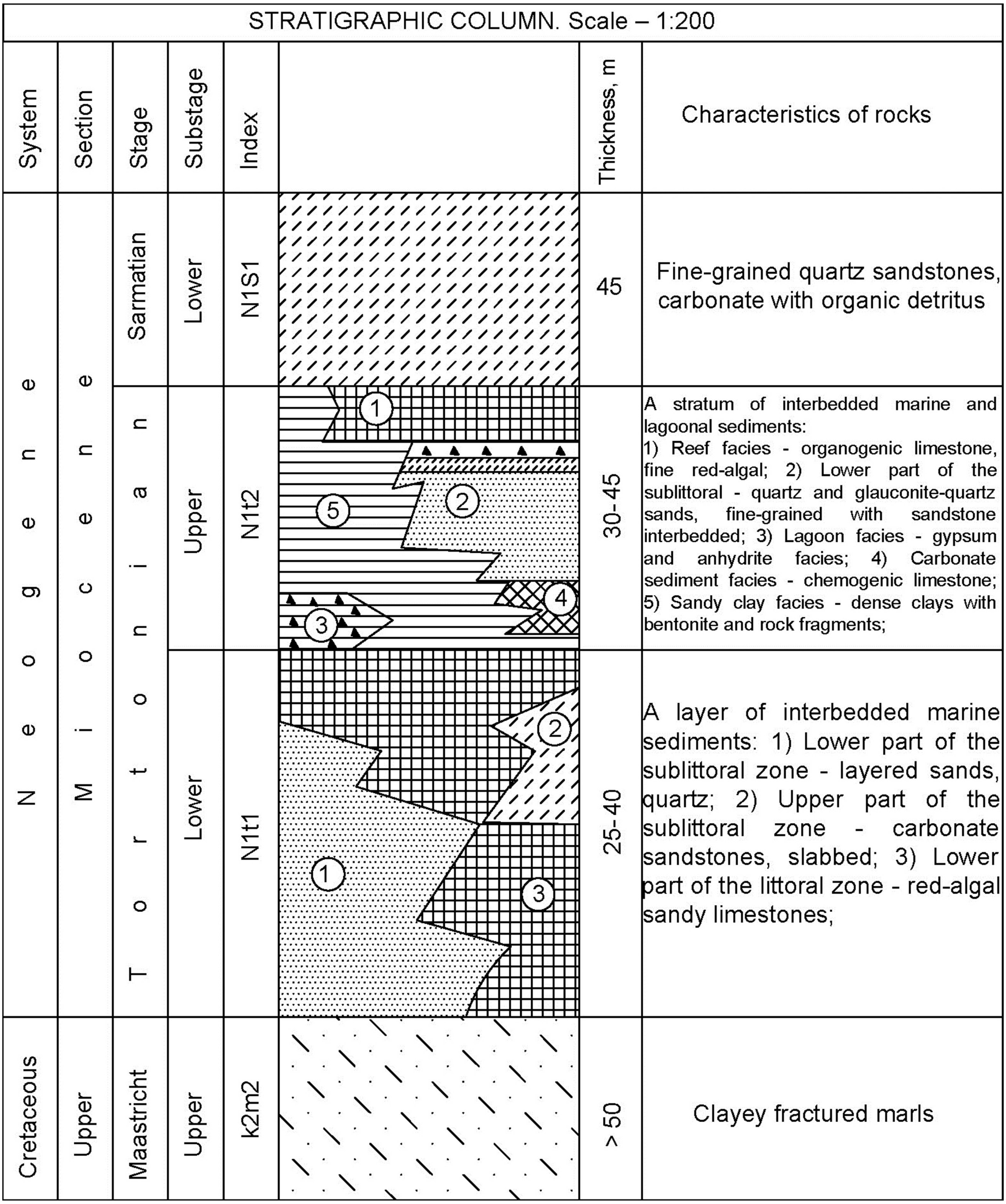

Fig. 7. Stratigraphic column.

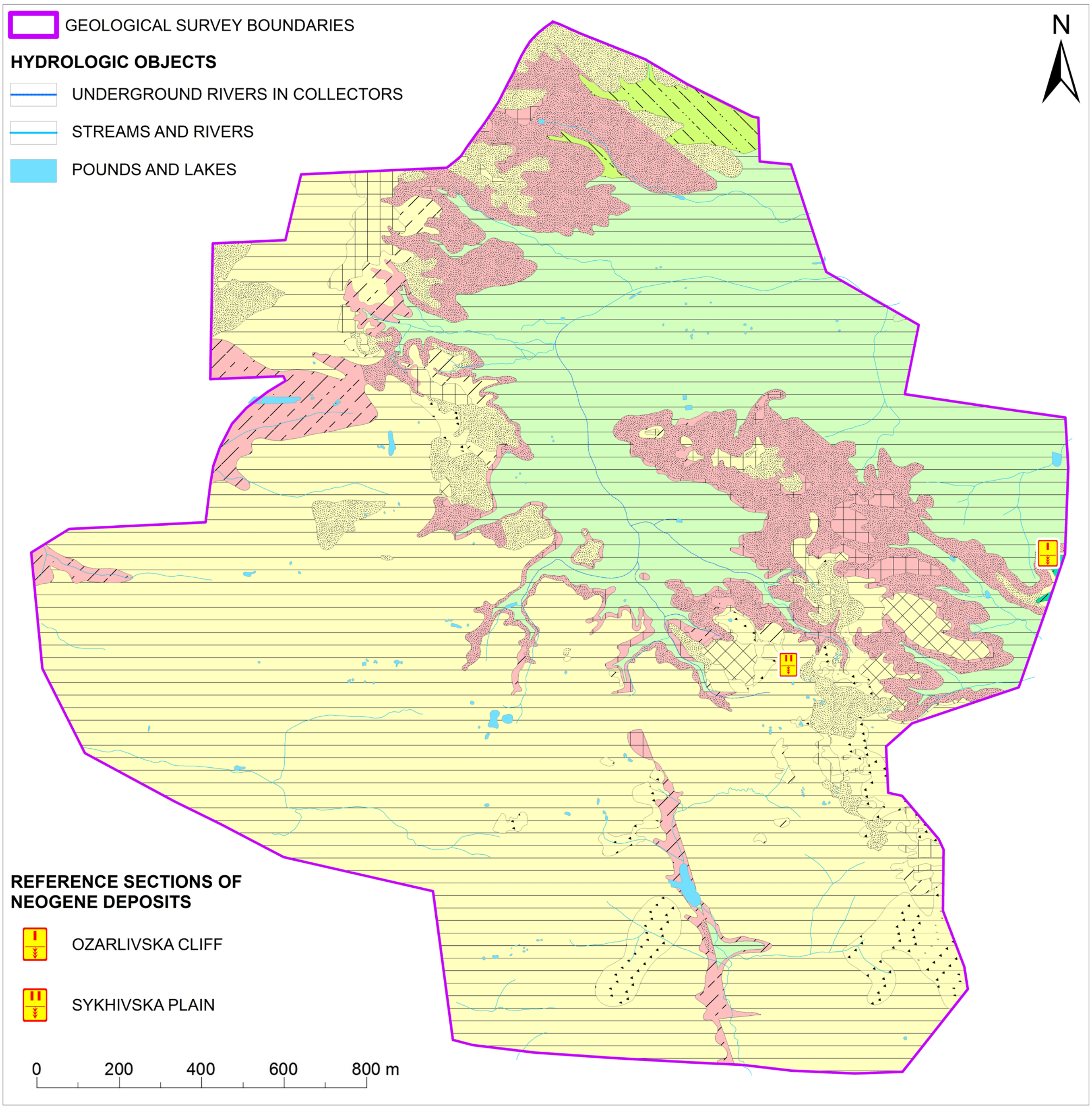

Fig. 8. Lithological-geological map of the bedrock of the city of Lviv.

The marls of Lviv contain an extensive complex of micro- and macrofauna, based on which it has been established that they belong to the upper part of the Maastricht stage, and the so-called ***Belemnitella junior*** zone. (Gruzman, 1980).

The described Cretaceous complex stands out as an independent stratigraphic-genetic complex in engineering-geological terms. Its importance for future construction is especially great in the vast valley of the Poltva River, where intensive civil and residential construction is currently taking place, and where it forms a bearing base (up to 20 m deep) for all types of foundations. The Cretaceous age marls composing this complex have several specific geotechnical properties, which are the object of study during engineering-geological surveys in the Poltva River valley. It has no impact on design and survey work in other areas due to the deep burial of this complex.

Table 1. Engineering-geological elements of the Upper Cretaceous complex.

EGE	Description
Marl	The sedimentary rocks is grey, weakly weathered, low-strength, softening, swelling, fractured, fractures without filler, fracture walls tinny, massive texture, fracture smooth, and mostly watered. The marl often delaminates and disintegrates when saturated with water.

Table 2. Geotechnical properties of rocks of the Upper Cretaceous complex.

№	Indicators of geotechnical properties	Marl
1	Density, γ_o (t/m³)	2.63
2	Bulk density, γ_c (t/m³)	2.12
3	Soil carbonate, (%)	48
4	Tensile strength in uniaxial compression at water-saturated state, R_c (MPa)	7
5	Tensile strength in uniaxial compression at natural water content, R_c (MPa)	9
6	Tensile strength in uniaxial compression at air-dried state, R_c (MPa)	15
7	Weathering coefficient	0.90
8	Softening coefficient	0.15
9	Degree of saturation, S_r (%)	0.89
10	Swelling coefficient, (%)	3.7

Clay complex of the weathering crust (ek_2m_2). This complex is widespread in the northern and central parts of Lviv (Figs. 6, 7, 8). This is the Poltva River valley and the dissected northern slope part of the Lviv plateau according to the taxonomy of geomorphological zoning. The thickness of sediments is mainly 1-2 m and only at the sides of the Poltva valley, and in some cases of the valley itself, it increases up to 10-11 m. This is explained by the fact that from the valley sides, the sediments were partially swept away by denudation processes, while in the Poltva Valley, they are developed and preserved intact in the near-slope areas and some parts of the valley. The deposits are characterized by the content of clastic material, which varies from single inclusions in the roof to 30-40 % at the bottom. Different $CaCO_3$ content in soils determines their different dispersibility and plasticity, and consequently their classification indices. It was not possible to establish any regularity in the spatial distribution of hard and half-hard loams, and hard and half-hard clays. The geotechnical properties of the selected nomenclature soil types are described below (Gruzman, 1980).

The Neogene complex (N) is lithologically the most complex and consists of a motley mix of a significant number of sedimentary rocks from different facies zones of the open sea. Neogene rocks are ubiquitously developed within the Lviv Plateau, the Roztocze Ridge, the Bilohiria-Malchytska Valley, the Zubra River Valley, and are absent in the Poltva River valley and on the loess Vynnyky and Malekhivska ridges.

Table 3. Geotechnical properties of clayey soils of the weathering crust.

№	Indicators of geotechnical properties	Half-hard loam	Hard loam	Half-hard clay	Hard clay
1	Bulk density, γ_c (t/m³)	1.93	1.85	1.89	1.92
2	Porosity, e	–	0.80	–	–
3	Degree of saturation, S_r (%)	0.28	0.22	0.29	0.25
4	Modulus of deformation, E_o (MPa)	4.9	6.4	5.3	6.9
5	Specific adhesion, C (KPa)	39.2	41.1	37.5	38.2

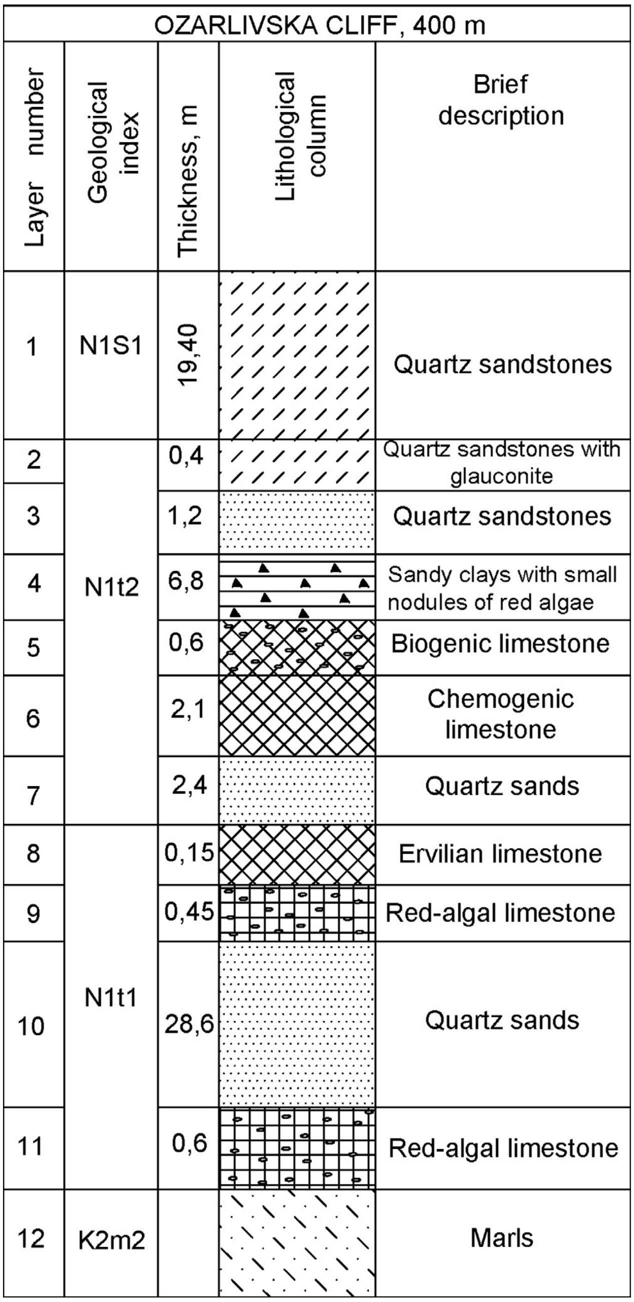

Fig. 9. Reference section of the Neogene strata of the Lviv city "Ozarlivska Cliff".

The Neogene complex is traditionally divided in age into two parts, corresponding to the supra-Ervilian and sub-Ervilian layers of the Lomnicki Formation (Lomnicki, 1897). The lower part belonging to the Lower Tortonian Substage is combined into the Opolian horizon, and the upper part comprising the Upper Tortonian Substage is allocated to the Tyrassic horizon. These strata are separated by a peculiar Ervilian horizon, which in the conditions of Lviv city serves as a marking age reference. However, it should be noted that the position of this horizon in the regional plan for the Neogene complex of the Ciscarpathian region contradicts many factors and its marking position was not recognized by several geologists. The most complete section of the Neogene complex was uncovered by a borehole on the Ozarlivska Cliff (Fig. 9) and this section was the reference for mapping the Neogene strata of the Lviv city.

The Lower Tortonian deposits (N_1t_1) on the territory of Lviv city include deposits of the following facies zones (Figs. 6, 7, 8):

- The lower part of the sublittoral zone of the sea – quartz sands;
- The upper part of the sublittoral zone of the sea is quartz sandstones;
- The lower part of the littoral zone of the sea – lithothamnium sandstones and limestones;
- Deposits of the desalinated sea – sandstones and limestones with Ervilia pusilla Phil.

1. Deposits of the lower part of the subtidal zone, known in previous schemes as the Mykolaev or Opillia layers, are represented by sands of various grain sizes and make up most of the lower Tortonian section. The greatest thickness of sandy sediments is confined to the eastern and south-eastern parts of the territory – on the Sykhivska Plain, it reaches 32–40 m (Fig. 10).

Geologist Leonid Kudrin divided the entire thickness of sandy sediments into two parts, formed in different facies conditions: the facies of sandy sediments of the open sea and the complex of submarine deltaic facies (Kudrin, 1966). The Lower Tortonian sands on the territory of the city of Lviv are considered by many researchers as submarine deltaic deposits. The basis for this conclusion is the presence of cross-bedding and fragments of silicified wood, devoid of bark, which is considered a sign of river transport of sands. However, a more or less detailed study of cross-bedding in numerous quarries in Lviv city showed that the layered formations of sublittoral sandy sediments are distinguished by internal structure features that contradict their classification as submarine deltaic textures. Vertical alternation of a series of different thicknesses without visible or significant changes in the granulometry and thickness of the constituent layers is quite common for cross-bedded deposits. The rule is a subparallel horizontal occurrence of serial seams. Although there are relatively frequent cases of displacement of the boundaries of obliquely layered series, in which the series has the appearance of concave, less often convex inclined lenses with a larger or smaller radius of curvature. Bedding is either unidirectional or alternately multidirectional; S-shaped cross-bedding is widespread along the direction of layers in adjacent series. All these features are not characteristic of deltaic layering,

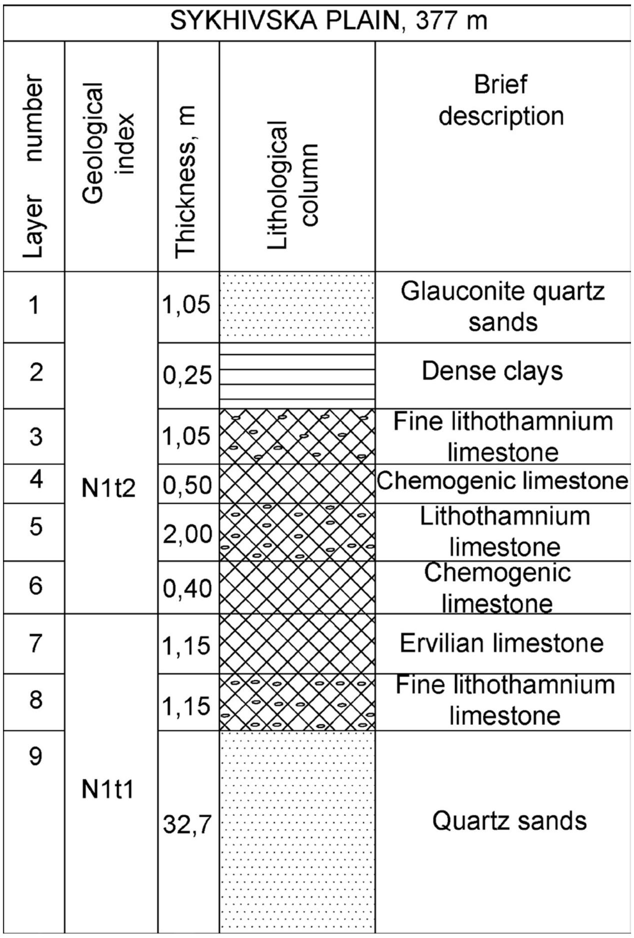

Fig. 10. Reference section of Neogene strata of Lviv city "Sykhivska Plain".

and even in the description of the latter, which is given by geologist Leonid Kudrin, one of the main features of submarine deltaic accumulation is missing – the cross, imbricated shape of serial sutures of cross-bedded units. There were no cases of confinement to the surfaces of the boundaries of a series of plant detritus, so common for the layering of river fans. Also unusual for deltaic formations is a typical detail of the internal structure of the Lower Tortonian sands: the separation of layers of the same order in thickness into packs or series, which alternate with non-layered strata, sometimes reaching impressive thicknesses of 12–15 m.

Thus, the nature of the internal structure of the Lower Tortonian sands on the territory of Lviv city makes us consider this entire sequence to be a single genetic formation, formed under conditions of quiet sedimentation of the open sea, in some areas of which the bottom currents arose with the formation of an inclined-layered texture. Bottom sediments reach their greatest thickness in the south and southeast of the territory, where they are 35–40 m.

Among the sands of the Sykhivska Plain, the light fraction is about 99.9 %, and the heavy fraction is 0.1 %. The light fraction is practically monomineral: the quartz content ranges from 99.4 to 100 %. Glauconite, feldspars, and carbonates with a total content of 0 to 0.6 % are present as impurities. Particles of carbonate material and fractions with a grain size of up to 0.5 mm are absent or present in negligible quantities in the form of a cementing mass. Feldspars contained in sands are essentially potassium in composition.

The lithologic-facies isolation of sandy deposits as part of the Lower Tortonian cycle made it possible to identify them as an engineering-geological element of the Lower Tortonian stratigraphic-genetic complex.

2. The upper part of the sublittoral zone includes quartz sandstones, which in some areas form rock and bedrock outcrops such as armored surfaces. They make up the Lower Tortonian section within the Western planning area, replacing a thick layer of sand. They are covered everywhere by Upper Tortonian clays and gypsum. In all other sections, they occur in the form of frequent interlayers of varying thickness (from 0.1 m to 10 m) among the quartz sands of the lower Tortonian.

The colour of the rocks varies from light yellow, and gray to greenish-gray. Studies of sandstones in thin sections using the immersion method showed that their composition is monomineral sandstones. The grain size is 0.01–0.1 mm, which determines the silty structure of the rocks. The composition of the clastic part includes glauconite. Fine- and medium-grained sandstones predominate according to mechanical analyses.

A feature of the rocks of this facies is the almost universal, but extremely uneven content of coarse clastic material of black chert. In some areas, there is a spotty alternation of interlayers and lenses of different sorting of grains, up to the identification of gravel packs. Quite often in sandstones, there is an accumulation of broken shells or large fragments of thick-walled fauna, as well as single fibrous concretions of red algae. As the amount of the latter increases, the sandstones are replaced by shallower formations compared to the previously described sands and were deposited in the intermediate zone between the sublittoral (quartz sands) and littoral (lithothamnium limestones) facies.

Sublittoral sandstones stand out as a strong engineering-geological element in engineering-geological terms. Their importance in this regard is increased by the fact that in several places they emerge on the daylight surface and can serve as a rock foundation for building structures.

3. The main feature of the deposits of this facies zone is the presence of organic remains from the class of red algae. The traditional name of these rocks (lithothamnium limestones and sandstones) is because it was initially believed that the red algae in them were represented only by the Lithothamnium species. But later, geologist Vladimir Maslov showed the widespread distribution of other representatives of red algae – Lithophyllum and Mesophyllum. Therefore, geologists began to call them red-algal limestones and sandstones. Red-algal rocks occupy very different positions in the sections of the Lviv Tortonian – at the base of the Opillia horizon (the central part of the Lviv plateau), at the top of the horizon (Roztocze ridge), sometimes completely composing the section of the Lower Tortonian (eastern part of the Lviv plateau). Red-algal rocks are present both at the base and at the top of the Lower Tortonian in the most complete Neogene section (in the borehole near the Ozarlivska Cliff). Three layers of lithothamnium limestones were found in sections of the Northern planning area. The thickness of the rocks is generally small (up to 4 m), except for those sections where red-algal rocks entirely compose the Lower Tortonian section, and then their thickness increases to 18 m.

The sediments of this facies are composed of concretionary red-algal limestones and sandstones. Coarse layering is often observed in them due to the different nature of cementation of the underlying nodules or their coarseness. Massive varieties occur besides concretionary varieties, connected by gradual transitions. The rocks are generally light grey to yellowish grey in colour, usually coarsely slabbed. The diameter size of red-water nodules reaches sometimes 10 cm. The histological structure of the algae, consisting of pelitomorphic calcite and characterized by sheaf-like arrangements of sieve-like rows, is visible in the splits. The bottom rocks are characterized by a constant admixture of clastic material consisting of poorly sorted and variously fossilized sandy fragments of quartz, glauconite, feldspars, and flints.

Red algal rocks were formed in areas of shallow water, in the zone of tidal action at a depth of not more than 60 m, accessible to the influence of solar radiation, as evidenced by the lithological composition of rocks and ecological features of red algae. In addition, the red-algal rocks were deposited on uplands of the chalk substrate, where sunlight penetrated and in this case, they are characterized by the presence of uncemented or weakly cemented nodule varieties. Red-algal (lithothamnium) limestones along with the described sandstones form another class of rocks in the Lower Tortonian complex. Although they are connected by various transitions, their engineering-geological properties are sharply different, which necessitates their separation.

Sandy-calcareous rocks with a massive accumulation of internal cores and shells of Ervilia pussila Phil belong to the deposits of a desalinated, regressive basin. These sediments have been given an important stratigraphic position since Lomnický's time and are usually isolated as an independent stratum. Certain facts emerged in the process of large-scale surveying that contradict the marking significance of the layers with the Ervilian fauna. These rocks occur everywhere on the boundary of the Upper and Lower Tortonian on the territory of the Lviv city and therefore they were considered as a separate horizon during the works. Ervilian deposits are distributed only in the eastern part of the studied area – on the Lysennytska and Ratyn uplands and the northern planning area. The maximum thickness of Ervilian deposits was recorded in the section of Zamkova Hill (1.1 m), in other places it varies between 0.1–0.7 m. The poverty and specificity of the species composition of the fauna of the Ervilian layers indicate unfavorable living conditions associated with the sharp shallowing and significant desalination of the basin at the end of the Lower Tortonian time. The water salinity was no lower than 17 ‰. The lithological composition of the deposits and the large accumulation of remains of sessile benthos indicate a slow rate of sediment accumulation and conditions of sea regression. Deposition of the Ervilian layers ends the Lower Tortonian sedimentation cycle (Gruzman, 1980).

The identified lithological-facial features of the Lower Torton sediments allowed the engineering-geological survey to segregate them into a separate stratigraphic-genetic complex consisting of several engineering-geological elements. Although the Lower Tortonian soils act directly as a bearing basement in a limited area (mainly on the slopes of uplands), they are involved in the sphere of the impact of engineering structures in most of the territory of Lviv, which predetermined the need for stratigraphic and lithological-facial study of these rocks for geotechnical purposes.

Upper Torton (N_1t_2). The next cycle of sedimentation in the study area is associated with the Upper Tortonian transgression, which completely covered the studied area of Lviv and had the greatest development here (Figs. 6, 7, 8). On the territory of Lviv city, there are several reference sections, which formed the basis of the classical scheme of stratification of the Upper Torton – Ratynska Upland, Kartumova Hill, Zamkova Hill, and Snopkivsky Range.

Table 4. Engineering-geological elements of the Lower Torton deposits.

EGE	Description
Limestone	Organogenic, organogenic-clastic, strong, fractured, cavernous, white with a greenish tinge, 8-10 m thick.
Sandstone	Sandstones are fine-grained, greenish grey on clayey cement, carbonate, and fractured, with the inclusion of freshwater fauna in the southwest. Sandstones are grey and light grey, weathered, and fractured, with interbeds of strongly fractured sandstone within the Kleparivska Upland. Sandstones can be used as a natural foundation for buildings and structures.
Fine sand	Sand is fine with thin interlayers and nests of dusty and medium, low-moisture, medium density, yellowish-grey, and light grey, quartz, in the lower part of the layer with crushed limestone and sandstone up to 40 %, up to 8.5 m thick. The sands can serve as a natural foundation for buildings and structures, as well as a bearing layer for pile foundations.
Dusty sand	The sands are greenish and light yellow, weakly yellow, medium to dense, homogeneous, low-moisture, up to 5.1 m thick. The sands can be used as a natural foundation for structures.
Medium sand	The sands are yellowish and bluish-grey, water-saturated, medium density, quartz-feldspar, semi-calcareous, and homogeneous. The sands can be used as a natural base for buildings and structures.

Table 5. Geotechnical properties of rocks of the Lower Torton.

№	Indicators of geotechnical properties	Limestone	Sandstone
1	Coefficient of non-uniformity, C_u	0.11	0.19
2	Density, γ_o (g/cm³)	2.72	2.67
3	Bulk density, γ_c (g/cm³)	2.39	2.4
4	Porosity, e	12.5	8.3
5	Water absorption, w_{abs} (%)	5.05	–
6	Tensile strength in uniaxial compression at dry state, R_c (MPa)	15.8	13.7
7	Tensile strength in uniaxial compression at water-saturated state, R_c (MPa)	13.8	10.8

Table 6. Geotechnical properties of sandy soils of the Lower Torton.

№	Indicators of geotechnical properties	Fine sand	Dusty sand	Medium sand
1	Coefficient of non-uniformity, C_u	0.24	0.25	0.25
2	Water content, W (%)	–	26	–
3	Degree of saturation, S_r (%)	0.28	0.30	0.83
4	Theoretical resistance index, R_o (MPa)	13.8	–	–
5	Porosity, e	0.7	0.64	0.59
6	Internal friction's angle, φ (°)	35	26	35
7	Bulk density, γ_c (g/cm³)	1.70	1.91	1.99
8	Specific adhesion, C (KPa)	1.96	1.72	1.98
9	Modulus of deformation, E_o (MPa)	24.5	14.3	17.2

The dissection of the Upper Torton deposits in the area of Lviv city is presented as follows:

I. Facies of the open sea:

- Upper part of the sublittoral – reefogenic facies: shallow lithothamnium limestones,
- The lower part of the sublittoral – quartz and glauconite-quartz sands.

II. Lagoon facies:

- The phase of sulfate sediments – gypsums, anhydrite.
- Carbonate sediments – chemogenic limestones.

III. Transitional facies:

- Sandy-clayey sediments - dense clays with interlayers and nests of sandstones, with fragments of karst rocks (limestone, gypsum).

1. The presence of reefogenic deposits in the Upper Torton in the territory of Lviv city confirmed the existence of a reef ridge in the southwest of the East European Platform. In the area of works, this facies is represented mainly by fine concretionary lithothamnium limestones of grey colour on clay cement and consists of a heterogeneous accumulation of small nodules and their fragments

of 0.5 to 5 mm size cemented by clay-carbonate mass. Occasionally, limestones gradually change to layered grey and greenish-grey clays and small nodule red algae. Under the microscope it can be seen that the rock consists of small nodules and fragments of red algae, to which foraminifer shells and fragments of corals and mollusks are mixed in subordinate quantities. The thicknesses of these deposits vary from 1.0 to 5–6 meters.

These rocks compose the most elevated parts of the relief and can be traced in a discontinuous band, starting in the south-east of the territory (Sykhivska Plain and Ratynska Upland) at 360–370 m and ending in the northern spurs of Kleparivska Upland at 350–380 m. The width of the strip in the widest part reaches 2.5–2.8 kilometers and the narrowest (Zamkova Hill and the western part of the Northern planning area) is 0.5–0.8 kilometers.

A large deposit of bioherm-type riffogenic rocks was identified during the works, located within the northern spurs of the Kleparivska Upland and the western part of the Goloskivska Upland and confined to an anticlinal uplift of the Cretaceous substrate. The central part of the bioherm, located at the maximum elevations of the territory, forms an armored site. It is composed of slabby recrystallized fine lithothamnium limestones with subhorizontal positions of planes of separateness.

The identification of reefogenic deposits in the cycle of the Upper Tortonian transgression makes geotechnical sense in that in several places they serve as a rock base for housing and civil engineering. Therefore, the geotechnical properties of these soils due to genetic features are important for the engineering-geological characterization of these areas.

2. As a single genetic formation, the Upper Tortonian sublittoral sediments consist of a variegated combination of essentially clastic sediments. The main role in this complex is played by multigrain quartz sands, always well pelletized, greyish-green due to insignificant but notable admixture of glauconite. Compacting, the sands are replaced by sandstones of the same composition, which in some cases represent the entire section of the sublittoral zone. Often the composition of sandstones changes towards an increase in carbonateness and an increased role of cement in the rock texture. These varieties are distinguished by an increased content of organic and plant detritus and an accumulation of internal lamellar gill nuclei. Rapidly disappearing interlayers and lenses of gravel and pebble material are observed in some sections.

Having a similar material composition, the Upper Tortonian sands on the territory of Lviv city differ in the conditions of occurrence. They have a continuous area distribution in the east of the territory, on the elevated side of the Lysennytska tectonic zone. In the central part of the district, in the area enclosed between two faults (Lysennytsky and Zubrovsky), sands lie in a complex interlacing with reefogenic lithothamnium limestones and lagoonal “ratynsky” limestones, nevertheless quite often forming independent fields. In the western part of the studied area, sands have no independent position and are subordinate to the clayey stratum, forming more or less extended and thick interlayers.

3. Sulfate deposits of gypsums and anhydrites are of particular importance for the assessment of the area for prospective construction. Long-term studies of sulfate rocks in the Precarpathian region have revealed a great variety of petrographic varieties: anhydrites, gypsums, gypsoanhydrites, sulphate-carbonate rocks, sulphur-bearing and ore-free limestones. Even greater diversity is revealed in the morphological structure of rocks – up to 12 types of structures are distinguished.

The sulfate strata on the territory of Lviv are spread in the west and south: starting at the headwaters of the Bilohiria-Malchytska valley it covers the western and southern outskirts of the city in a giant semicircle, composing the territory of the South-Western planning district, the Southern planning district and the outskirts of the Sykhivska Plain. In its composition anhydrites are dominant, and gypsums and transitional varieties – gypsoanhydrites – are much less widespread. There are no indications of other petrographic varieties. The thickness of sulfate rocks naturally increases to the west, where it reaches 13 meters.

There is no zoning of lithological and petrographic types of gypsum-bearing formations and data of specialized studies of sulfate rocks on the territory of Lviv city. It follows from descriptive works that of petrographic varieties gypsums have the greatest predisposition to karst formation, and of textural-structural types – coarse-crystalline types – columnar, sheaf-shaped, radial-radiate, needle-shaped, twin-like. But at the same time, anhydrides are subject to hydration processes, which can also cause karst formation.

4. The studied area contains a stratotypic section of sediments of lagoonal carbonate facies, the location of which gave the name to these rocks – Ratyn Hill. Here the greatest thickness of these limestones on the territory of Lviv (14 m) was uncovered. Ratyn limestones form dense hard rocks

of grey, creamy- and brownish-grey colour, often with significant clay admixture, detectable by dark grey colouring and the earthy surface of fresh chipping. Very often they bear traces of marked calcification. Limestones are characterized by a pelitomorphic structure and their grain size does not exceed 0.01 mm. Very often limestones reveal various kinds of clotted structures characterized by sometimes complex textural patterns. The usual clot structure consists of the presence of pelitomorphic lumpy clots with vague outlines of calcite. Sometimes the clots have the character of vein-like formations, intricately branching in the rock mass. Connecting, they form a fine-mesh network, the cells of which are made of fine-grained calcite.

5. The characteristics and conditions of sandy-clay deposits have been reported previously. It should be added that under the microscope the main mass of these rocks is composed of clayey material with an admixture of carbonate and is characterized by a pelitic structure. It contains thin phenocrysts of pyrite and carbonized plant detritus. The sulphate component gives lenticular and rounded formations revealing an aggregate structure. At the same time, the carbonate-clay matter of the main mass seems to flow around anhydrite inclusions, which determines the glass structure of clays (Gruzman, 1980).

Genetic peculiarities and stratigraphic independence allowed the described rocks to be identified as an independent stratigraphic-genetic complex. The lithological diversity of the Upper Tortonian rocks ensured the separation of a large number of engineering-geological elements with different geotechnical properties in this complex. The Upper Tortonian marine stratigraphic-genetic complex is not only the most complex, where all engineering-geological types of soils are combined, except for peat soils but also has the largest area distribution on the territory of Lviv.

Table 7. Engineering-geological elements of the Upper Torton deposits.

EGE	Description
Sandy limestone	Moderately weathered, strongly fractured, fractures 0.1–1 cm in size are randomly orientated and filled with sandy-clayey material with faunal remains. The thickness of sandy limestone is 1.8–2.8 m.
Chemogenic limestone	Low-strength, homogeneous, fractured, on clay cement, whitish grey. The thickness is from 0.8 to 4.0 m.
Gypsum	Crystalline, smoky, moderately weathered, and fractured – fractures up to 5 cm wide, watered along the fractures, karst phenomena are developed. Caverns are sometimes filled with tight and soft plastic clay with lenses of dusty sand. Gypsum thickness ranges from 1.8 to 13 meters. Fractured pressure waters are found in gypsums. Gypsum under load can cause uneven settlement of foundations due to uneven cavernousness in the plan.
Sandstone	Fine-grained, dense, on clay and lime cement, fractured, fractures of different densities, mainly vertical. Fractures of different widths – hair-like and thin up to 1 mm, less often 2-5 mm, and single fracture 5–20 mm. The fractures are closed, and some are filled with clayey material. The thickness of sandstones is up to 8.2 m. It is a water-bearing rock, fractured water is present. Sandstones occur below the active zone of buildings.
Medium sand	Medium-sized, water-saturated, medium-density, heterogeneous, yellowish-grey sands. They occur in the roof of Upper Tortonian deposits, and underlying gypsums, occur among gypsums. It can serve as a natural foundation for buildings and structures.
Fine sand	Sands are yellowish and light grey, fine with thin interlayers and nests of dusty and medium, low-moisture, medium density. The sands can serve as a natural foundation for buildings and structures, as well as a bearing layer for pile foundations.
Dusty sand	The sands are greenish-yellow, dense, water-saturated, glauconite-quartz, with interlayers and lenses of sandy loam up to 10 cm thick. The sands are water-bearing rocks. Underground waters are not aggressive in all types of corrosion. The sands can be used as a natural foundation for buildings and structures.
Hard clay	The clay is greenish-grey, lumpy with sandstone fragments. Clays can serve as a natural foundation for buildings and structures.
Half-hard clay	Clays are greenish and bluish-grey, strongly sandy, with interlayers of weakly cemented sandstone, with fragments of limestone, with nests of bentonite. The clays can serve as a natural foundation for buildings and structures.
Stiff-plastic clay	Medium compressible clays of greenish-grey colour, lumpy, heterogeneous in composition, with frequent bentonite inclusions. The clays can serve as a natural foundation for buildings and structures.
Hard loam	Loams can serve as a natural foundation for buildings and structures.
Half-hard loam	
Stiff-plastic loam	

Table 8. Geotechnical properties of rocks of the Upper Torton.

№	Indicators of geotechnical properties	Sandy limestone	Chemogenic limestone	Gypsum	Sandstone
1	Tensile strength in uniaxial compression at air-dried state, R_c (MPa)	–	–	–	0.4
2	Tensile strength in uniaxial compression at dry state, R_c (MPa)	–	18.5	13.0	24.5
3	Tensile strength in uniaxial compression at water-saturated state, R_c (MPa)	28.4	12.6	8.2	0.15
4	Softening coefficient	–	–	–	0.50

Table 9. Geotechnical properties of sandy soils of the Upper Torton.

№	Indicators of geotechnical properties	Medium sand	Fine sand	Dusty sand
1	Degree of saturation, S_r (%)	–	0.24	–
2	Porosity, e	–	0.63	0.59
3	Natural slope's angle dry (°)	32	33	39
4	Natural slope's angle underwater (°)	29	32	35
5	Bulk density, γ_c (g/cm³)	1.65	–	2.0
6	Specific adhesion, C (KPa)	1.96	1.96	4.0
7	Modulus of deformation, E_o (MPa)	27.9	–	23.6

Table 10. Geotechnical properties of clayey soils of the Upper Torton.

№	Indicators of geotechnical properties	Hard clay	Half-hard clay	Stiff- plastic clay	Hard loam	Half-hard loam	Stiff- plastic loam
1	Plasticity index, P_I	–	25	–	11	13	13
2	Water content, W (%)	–	27.4	23.8	18.8	22.6	
3	Density, γ_o (g/cm³)	1.89	1.95	1.95	2.02	2.03	1.90
4	Bulk density, γ_c (g/cm³)	1.44	1.54	1.60	1.70	1.63	1.49
5	Porosity, e	0.9	0.5	0.7	0.6	0.6	0.81
6	Degree of saturation, S_r (%)	0.96	0.93	–	0.87	0.95	0.93
7	Soil compaction index, k_{com} (KPa)	2.3	2.0	2.5	–	–	
8	Modulus of deformation, E_o (MPa)	9.1	9.9	9.6	9.8	–	–
9	Internal friction's angle, φ (°)	15	19	18	21	18	19
10	Specific adhesion, C (KPa)	42.9	42.5	43.7	54.9	32.6	27.5

Lower Sarmatian (N_1S_1). Sarmatian deposits are known only on the Ozarlivska Cliff, where they form rock outcrops up to 30 m high. In general, their thickness here is up to 50 m and they are represented by quartz sandstones of light grey colour, dense, multigrained with individual large quartz grains. The cement of the rocks is carbonate, the character of basal-type cementation (Figs. 6, 7, 8).

Discussion

Having characterized the geotechnical properties of stratigraphic-genetic complexes of bedrock in Lviv, it is proposed to discuss the most difficult in geotechnical respect engineering-geological elements, which require certain measures during construction development and organization of engineering preparation of the territory.

The Upper Cretaceous complex is represented by marl, whose geotechnical properties include a tendency to swell. The peculiarity of swelling soils is their ability to decompact and increase in volume when moistened. Subsequent decrease of humidity in such soils leads to shrinkage. Deformations of the foundation soil as a result of swelling and shrinkage may cause damage to construction objects. Water protection measures are implemented first of all to eliminate the negative impact of swelling soil on structures: site planning for drainage of rain and melt water and organized drainage of water from the roof of buildings. One method of eliminating swelling properties of the soil is pre-soaking, which results in raising the soil before construction to a level above which swelling deformations are eliminated. It is also allowed to build compensating sand cushions, for which sand of any coarseness is used, except for dusty sand. The compaction of sand in the cushions is carried out to the dry density ($γ_o$ = 1.6 t/m³).

The weathering crust is represented by clayey soils characterized by low values of deformation modulus (E_o = 4.9-6.9 MPa). In addition, these types of soils are mainly confined to flooded and non-flooded terraces of the Poltva River, which are characterized by high levels of groundwater table from the day surface. Sand cushions and slab foundations are recommended for these soils (Shutenko et al., 2015).

The gypsum column is identified among the engineering-geological elements of the Upper Torton deposits, which have a propensity for karst formation. Special engineering surveys for karst were carried out in the southern planning area of Lviv in 2020. Gypsum was found to be present in the geological section of the southern part of the city and saucer-shaped waterlogged depressions of karst origin were found on the surface. In this connection, the possibility of deformation of the earth's surface as a result of the collapse of karst cavity vaults or suffusion of loose material of overlying deposits into the cavity and expansion of fractures in gypsum is not excluded, especially if the natural regime of groundwater is disturbed. However, there is little evidence of karst on the earth's surface. No karst failures have been observed in the Southern planning area. Complications in the construction and operation of buildings and structures related to karst in Lviv and its immediate vicinity are practically unknown. Therefore, the following activities are recommended:

1. Do not locate buildings and structures over identified underground cavities of significant size or grout these cavities, do not locate buildings and structures on or near identified surface and buried sinkholes;
2. It is necessary to choose to strip monolithic or prefabricated monolithic reinforced concrete foundations, to use foundations with support on rocks below the karst zone, to use pile-stocks and deep piles when supporting non-karst rocks (Tolmachev, 1986);
3. To prevent the activation of karst-suffosion phenomena it is extremely important to organize a thorough drainage of the storm and waste water from the construction area, to effectively control water leaks from utilities and to eliminate all boreholes exploiting the Neogene horizon, the zones of influence of which cover the territory of the southern planning area, as well as to prohibit the operation of new boreholes in the future (Gruzman, 1980).

Conclusions

1. Geotechnical characterization of soils is based on the identification and mapping of stratigraphic-genetic complexes of rocks, accordingly, the geological basis of engineering-geological surveys should be based on two factors – age (stratigraphic) and genetic. The age factor is regulated by regional stratigraphic schemes, there is no accepted scheme of genetic division of rocks. The main task of studying the geological structure of Lviv for geotechnical purposes is to identify specific features and criteria of the genetic division of rocks, corresponding to the specialization of works. It is necessary to distinguish stratigraphic-genetic complexes based on the adopted stratigraphic-genetic scheme of bedrock dissection.

2. Bed rocks are confined to certain geomorphological units, in connection with which at the primary stage it is necessary to geomorphological zoning of the territory of Lviv. Lviv belongs to the Volhynian-Podolian Region of strata-denudation uplands, in turn, within Lviv city there are two geomorphological subregions - Podolian structural-denudation upland on Cretaceous and Neogene deposits and Lower Pollisia strata-accumulative plain on Cretaceous deposits. These subregions are divided into 6 geomorphological districts and 13 subdistricts.

3. Lithological, paleontological and chronostratigraphic research methods were applied in the study of the stratigraphy of the bedrock of Lviv. Geotechnical methods included drilling and sinking of mine workings, field tests, and laboratory studies of soils.

4. The Cretaceous system is represented by rocks of the Upper Cretaceous complex (k_2m_2): clayey fractured marls with a high content of sponge spicules, fragments of inoceram shells and other detritus. The marls contain an extensive complex of micro- and macrofauna, based on which it was established that they belong to the upper part of the Maastricht Stage, and the so-called *Belemnitella junior* zone. The marl has specific swelling properties, therefore, rain and meltwater drainage, sand cushions, and preliminary soaking are necessary to eliminate this phenomenon. The clay complex of the weathering crust (ek_2m_2) lithological complex is represented by loams and clays. Clay soils are characterized by a small deformation modulus value and occurrence in waterlogged conditions, which requires sand cushions and the choice of slab foundations.

5. The Neogene system is represented by rocks of the Lower Torton, (N_1t_1) Upper Torton (N_1t_2), and Lower Sarmatian (N_1S_1). The Lower Torton

rocks are a thickness of interchangeable marine sediments: the lower part of the sublittoral zone is lithologically represented by laminated, quartz sands; the upper part of the sublittoral zone is represented by carbonate plate sandstones; the lower part of the littoral zone is represented by red-algal sandy limestones. The geotechnical characteristic of the rocks of the Lower Torton is satisfactory, all soils can serve as a natural base for buildings and structures. The rocks of the Upper Torton are a thickness of intermixed marine and lagoonal sediments: reef facies are represented by organogenic fine-lithothamnium limestones; the lower part of the sublittoral is represented by quartz and glauconite-quartz sands, fine-grained with sandstone interbeds; lagoonal facies is represented by gypsum and anhydrite facies; carbonate sediments facies is represented by chemogenic limestones; sandy-clay sediments facies is represented by dense clays with bentonite and rock fragments. Geotechnical characteristics of the rocks of the Upper Torton are as follows: gypsum is characterized by karst formation; sandstones lie below the active zone of buildings; sands, clays, and loams can serve as natural foundations for buildings and structures. The Lower Sarmatian rocks are represented by quartz fine-grained carbonate sandstones with organic detritus, which may well serve as natural foundations for buildings and structures, as they are quite strong.

6. Gypsum is the most problematic rock in geotechnical terms, as it is prone to karst formation. Surveys of buildings and structures that are located in the conditions of these types of rocks have not revealed any deformation, settlement, or emergency condition. However, avoidance measures, special types of foundations, and measures to prevent water leakage from utilities and liquidation of boreholes exploiting the Neogene aquifer are recommended for the Southern planning area of the city.

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