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USE OF GIS TECHNOLOGIES FOR ZONING URBAN AREAS TAKING INTO ACCOUNT ENGINEERING-GEOLOGICAL CONDITIONS

Nurgul Alibekova[1],*Assem Abisheva[1], Balganym Dosmukhambetova[1], Nargul Saktaganova[2], Uliya Abdikerova[2], Aigul Budikova[2]

[1]Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan
[2]Department of Architecture and Construction Production, Korkyt Ata Kyzylorda University, Kyzylorda, Kazakhstan

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ABSTRACT: To solve the problem of insufficient accounting of engineering-geological conditions and types of soils in the territory of the Republic of Kazakhstan, it is necessary to systematize and generalize information on engineering-geological conditions. This goal can be accomplished through the utilization of contemporary geoinformation systems (GIS), which enable the integration and examination of extensive datasets encompassing findings from drilling engineering-geological boreholes. The creation of a geoinformation database based on a dataset including a map of the city with specified X, Y, and H coordinates, as well as the results of drilling more than 500 engineering-geological boreholes studied from 2014 to 2022 in one of the main industrial cities of Kazakhstan, Pavlodar city, is an example of this approach. By analyzing the obtained data, the zoning of the territory with regard to engineering-geological conditions and soil types was carried out, five main engineering-geological elements (EGE) were identified, the physical-mechanical properties of soils were assessed, and engineering-geological maps of quaternary deposits and bedrock were created, as well as special geotechnical maps, including a map of groundwater level, which will help improve the quality of design and construction of buildings and structures in the city and in the whole territory of the Republic of Kazakhstan. Also, an analysis of the interaction of the soil base and strip foundations was carried out, and based on the results obtained, the optimization of design solutions through their typing, depending on the choice of geometric dimensions of the strip foundation base, was proposed.

Keywords: Zoning, Engineering-geological conditions, Types of soil, GIS, Geoinformation database

1. INTRODUCTION

Engineering-geological studies are aimed at forming an information model of the terrain, which should contain all the necessary data to solve problems related to the placement of construction facilities, the assessment of the impact of engineering-geological measures on the environment, and the planning of measures for its transformation. The last century has seen several significant advances in the field of engineering geology, which allowed for the expansion of the procedures of engineering-geological mapping as the main tool for obtaining data [1].

To date, geospatial data based on geographic information systems (GIS) are widely used worldwide for various purposes. For example, GIS is used for analyzing the probability of landslides and assessing the level of risk in complex landscapes [2,3], developing flood susceptibility maps [4], and creating information maps to prevent fires in forested areas under study [5,6]. They also enable the creation of interactive maps displaying the spatial distribution of various variables, such as seismic characteristics [7,8] and soil susceptibility to liquefaction [9]. GIS helps engineering geologists integrate different types of data, including digital maps, terrain models, and research findings, into a unified information model of the terrain.

A more comprehensive investigation of the engineering geological conditions is required in the Republic of Kazakhstan due to the presence of collapsible and saline soils [10]. Additionally, there is a need to study the anthropogenic alterations that result in the inundation of urban areas. The reduction of areas with favorable soils makes the issues of design, construction, and operation of buildings and structures in these conditions increasingly relevant. To ensure safety during construction, thorough engineering geological surveys are necessary to fully understand the complexity of the geological structure. The lack of information about geological conditions can pose a danger.

However, over the past 30 years, surveys and construction projects in major cities in Kazakhstan have not taken into account the geological conditions and properties of soils, leading to negative consequences for buildings and structures [11]. Modern conditions for conducting engineering geological surveys are characterized by an accelerated pace of work, limited conditions, and the requirement to obtain information in the shortest possible time with minimal costs. Additionally, existing data on engineering geological research is usually presented in paper format and may not always be easily utilized in practice. Given the current situation, there is an urgent need to create a geoinformation database for detailed analysis of the engineering geological conditions of the regional soil complex in one of the leading industrial cities of the Republic of Kazakhstan, Pavlodar. Pavlodar is one of the leading industrial cities in the Republic of Kazakhstan [12], primarily focused on aluminum production, oil refining, chemical, and metallurgical industries. In this regard, the city's development and implementation of large-scale construction projects become important factors for the economic development not only of the region but also of the entire country.

2. RESEARCH SIGNIFICANCE

The use of GIS for zoning the urban area, taking into account the engineering-geological conditions, is a very important study for the development of the city of Pavlodar and the formation of public policy in the field of industrial development in Kazakhstan. The creation of a geographic information database with information on soils and groundwater will provide a digital model of the urban area, which will help optimize the planning process for the urban environment. This, in turn, will save resources and reduce the cost of construction and operation of facilities, as it will be possible to choose the best locations for the construction of facilities and to determine the types of foundations, taking into account the engineering-geological conditions. Also, the use of GIS for zoning the city, taking into account the engineering-geological conditions, will help to assess the risks of negative geological processes, such as landslides, rockslides, flooding, etc.

3. DEVELOPMENT OF THE GEOINFORMATION DATABASE USING GIS TECHNOLOGIES

3.1 Methodology for Creating a Geoinformation Database

The Geoinformation Database program has a unique format for collecting engineering-geological survey data. The management system has a two-level hierarchical structure that includes functions for general management, data input control, data extraction and processing, and data addition [13].

The first level of the structure is an administrative function that provides general management and organization of the graphic process. The second level of the hierarchy consists of functions that perform preliminary processing of the initial information and ensure the organization of the graphic process.

The initial information used in the program is divided into two main sections [14]. The first section includes fixed datasets, which are informational materials that come directly with the program. These materials may include a city map, coordinates, and characteristics for obtaining graphic files.

The second section comprises initial data generated directly by the user and includes data obtained from engineering-geological surveys and entered into the program during execution. To enter this data, a map of the survey area is created in a CAD program, i.e., AutoCAD, and tabular data is prepared for each borehole, which is shown in Table 1. The data includes the depth of the deposit, the age and name of the soil that ensures the stratigraphy and subsequent location of the layers, as well as the coded state (if loose soil, then the code is equal to zero; if half-rock or rock is 1, 2, 3, 4, depending on the type of the rock soils), and information about alternating layers of soil (ex. alternating layers of sand and clay, "-SACL").

Table 1 Strata information

RBCODE	Lower Depth (m)	EGE	Soil Index	Soil Code
B001	0.4	1	tQ_{IV}	Pr
B002	3.6	2a	$adQ_{II\text{-}IV}$	LmSn
B003	5.7	5a	N	1Cl
B004	8.0	5c	N	3Cl
B005	10.8	5a	N	1Cl
B006	14.1	4	N	nSn

3.2 Study Area

Pavlodar is located in northern Kazakhstan and is the administrative center of the Pavlodar region. It was founded in 1938 and is currently the seventh-most populous city in Kazakhstan. Pavlodar is situated 450 km to the northeast of the capital Astana and covers an area of 217.845 thousand square kilometers. The city is a large industrial center with borehole-developed mining, metallurgical, and energy industries. Pavlodar region accounts for 7% of industrial production, 70% of coal mining, 3/4 of ferroalloy smelting, 40% of electricity generation, and the refining of petroleum products at the level of the Republic.

In geological and structural terms, the area of this city is located in the junction zone of two major geological structures: the Kazakh folded country (Saryarka) and the West Siberian Plain. The area has lake-alluvial deposits of Neogene age (N), which are subdivided into Pavlodar (N_{1-2}pv), Aral (N_1ar), and Kulunda suites (alN_{1-2}kln), overlain by Upper Quaternary and modern deposits of alluvial-delluvial and technogenic origins (tQ_{IV}).

Groundwater ranges from 1 to 17 m deep and is replenished by precipitation and flooding. However, in recent decades, the industrial zone of the city has experienced a rise in groundwater levels, causing erosion, waterlogging, and soil salinization. To address these problems, it is necessary to develop informed urban planning solutions and classify the city's engineering and geological conditions [15].

3.3 Typification of Engineering-Geological Conditions using GIS

The engineering-geological conditions were typified by conducting construction zoning based on the number of floors of residential buildings, as shown in Fig.1. Five zones were identified: multi-storey residential buildings, low-rise residential buildings up to 4 floors, private residential buildings, industrial zone, and green zone. The study focused on the zone for multi-storey building development in Pavlodar.

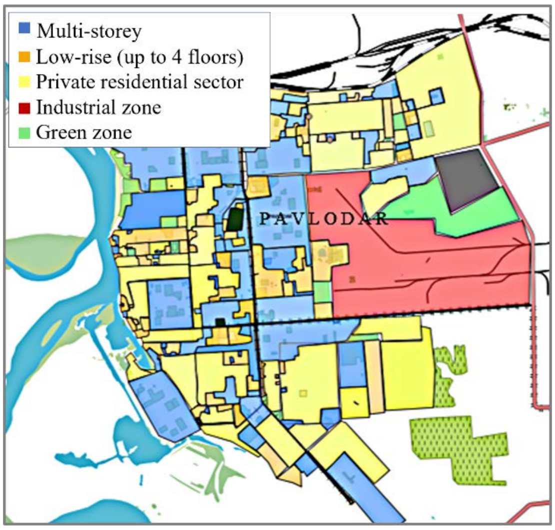


Fig.1 Scheme of construction zoning of Pavlodar

To create the "Geoinformation Database of Pavlodar", published materials from engineering-geological surveys carried out in Pavlodar were initially collected and analyzed. The data sources included information from 558 boreholes studied between 2014 and 2022, which provided details on the physical-mechanical properties of soils based on 2249 soil samples collected from the earth's surface to a depth of 25 m.

Further, with the help of the program "Geoinformation Database of Pavlodar," the geotechnical conditions of the soils of the built-up territory of the city were studied before a detailed survey, and five main engineering-geological elements were identified, various in origin and age (Table 2).

As a result of the division into engineering-geological elements, engineering-geological sections of maps (Fig.2) were obtained, reflecting the geological conditions of the construction of structures, with the help of which it is easy to determine the elements of occurrence, their layer thick (Fig. 2a, b, c, d), and the depth of occurrence at any point of the terrain (Fig.2e, f). This makes it possible to better characterize soils and rocks, such as their strength, water permeability, and other physical and mechanical properties.

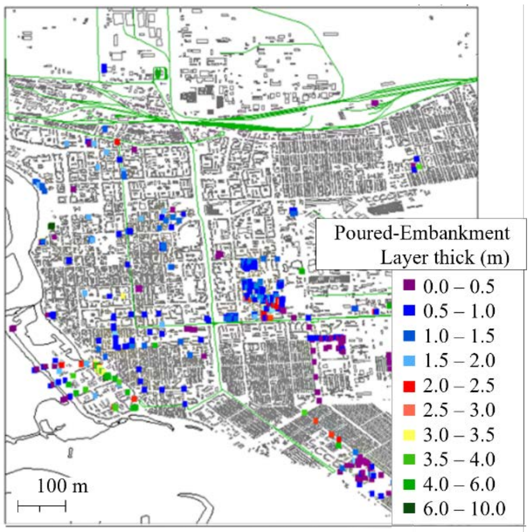


Fig. 2a The thickness of technogenic deposits of EGE-1

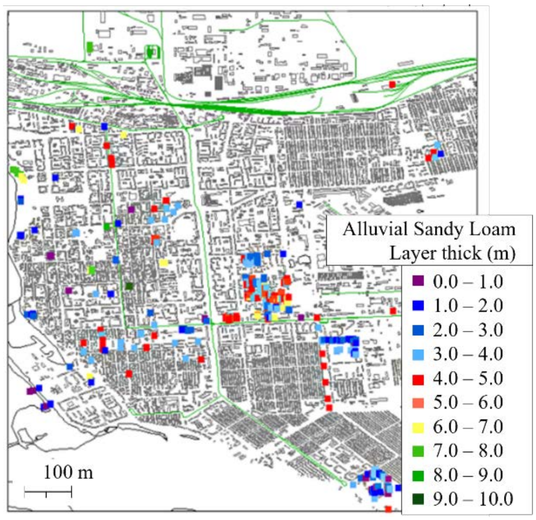


Fig. 2b The thickness of alluvial Sandy Loam soils of EGE-2a

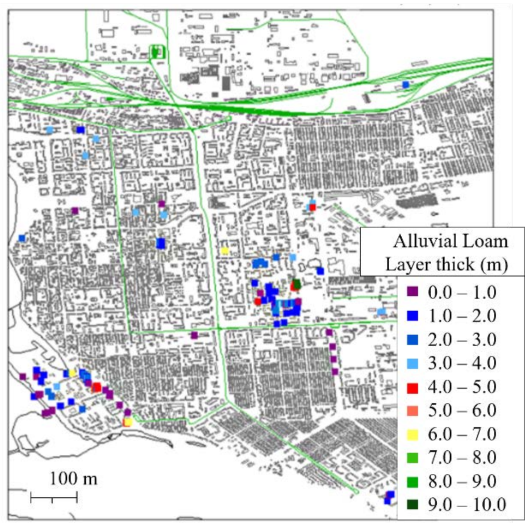


Fig. 2c The thickness of alluvial Loam soils of EGE-2b

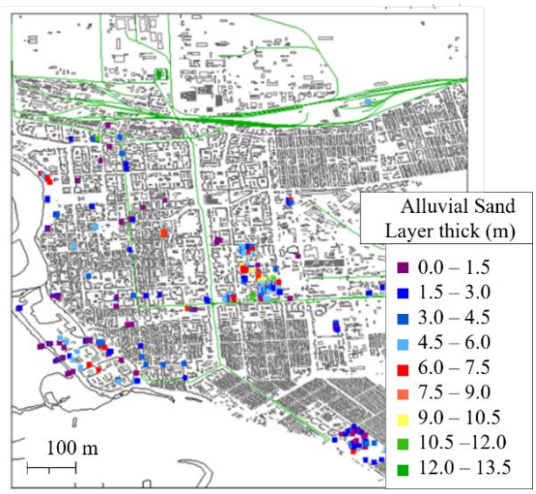


Fig. 2d The thickness of alluvial Sand soils of EGE-3

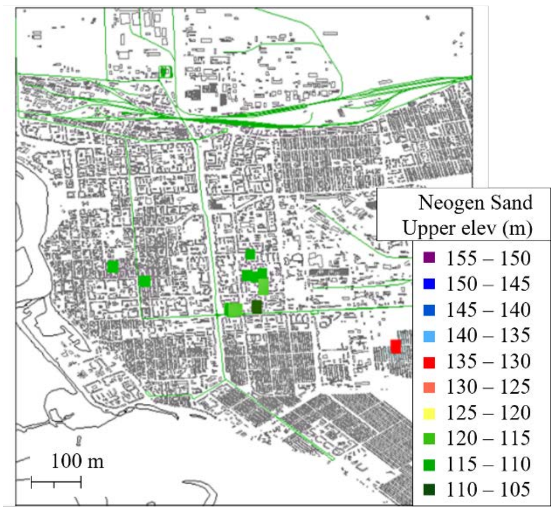


Fig. 2e The upper elevation of Neogene age of Sand soils of EGE-4

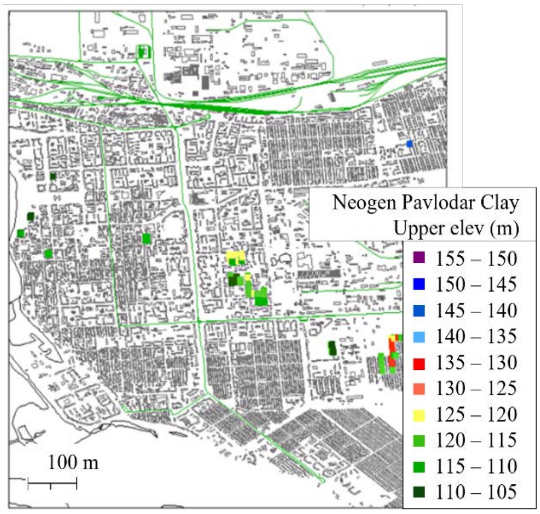


Fig. 2f The upper elevation of Neogene age of Pavlodar Clay of EGE-5a

Fig. 2 Engineering-geological maps according to the classification of soils of Pavlodar

Further, with the help of the program "Geoinformation Database of Pavlodar," the geotechnical conditions of the soils of the built-up territory of the city were studied before a detailed survey, and five main engineering-geological elements were identified, various in origin and age (Table 2).

As a result of the division into engineering-geological elements, engineering-geological sections of maps were obtained, reflecting the geological conditions of the construction of structures, with the help of which it is easy to determine the elements of occurrence, their power, and the depth of occurrence at any point of the terrain (Fig.2).

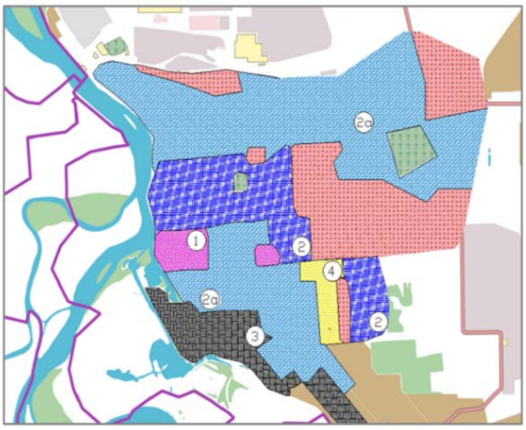
Also, it can be noted that the program "Geoinformation Database of Pavlodar" made it possible to divide the built-up area of the city into conditionally homogeneous zones according to the types of soil bases. It was revealed that the engineering-geological elements form about four types of soil bases before the bedrock (Fig.3).

In addition, a special geotechnical map of the groundwater level was built using the program "Geoinformation Database of Pavlodar" (Fig.4). Out of a total of 558 investigated engineering-geological boreholes, the groundwater level (GWL) was identified at different depths.

In 120 boreholes (approximately 21.5% of the total), the GWL was detected at a depth of up to 2.0 m. In 326 boreholes (58.4%), the depth of occurrence ranged from 2.1 to 5.0 m, while in 54 boreholes (20.1%), the depth of occurrence ranged from 5.0 to 10.4 m. These results provide important information for further design and construction in Pavlodar. For example, given that a significant part of boreholes have GWL at a depth of up to 2.0 m, in this case, additional studies are especially important to determine the variability of GWL at different times of the year. Periods of high humidity or precipitation can significantly affect this level, which may require taking appropriate precautions in projects related to drainage systems or waterproofing. How to shorten. In addition, attention should be paid to regions with a GWL depth of more than 5.0 m since they may need to take additional precautions to ensure the integrity of building materials and prevent water penetration.

Table 2 Physical-mechanical characteristics of EGE soils

Geological Index (Age)	Average Column of Soils	Soil type	Soil Code	Physical-mechanical characteristics					
				Bulk density ρ, g/cm^3	Moisture w, %	Porosity e	Elastic Modules E, MPa	Angle of internal friction ϕ, degree	Cohesion coefficient, kPa
tQ_{IV}	EGE-1a	Topsoil	Pr	1.40	-	-	-	-	-
	EGE-1b	Backfill	Emb	1.40	-	-	13.0	-	-
$adQ_{(II-IV)}$	EGE-2a	Sandy loam	SnLm	1.88	10.0	62.0	12.8	29.0	12.1
	EGE-2b	Loam	aLm	2.00	24.0	72.0	18.0	16.6	28.0
	EGE-3	Sand of various size	aSn	1.68	9.0	73.0	20.0	34.0	3.0
N	EGE-4	Sand of various size	nSn	2.03	22.0	60.0	35.0	32.7	2.0
	EGE-5a	Clay (Pavlodar suite)	1Cl	1.97	46.0	73.0	12.0	17.0	106.0
	EGE-5b	Clay (Aral suite)	2Cl	1.88	33.0	93.0	15.6	11.0	111.0
	EGE-5c	Clay (Kulunda suite)	3Cl	2.00	19.0	63.0	7.3	18.0	57.0



1 soil type	2 soil type	2a soil type*	3 soil type	4 soil type
EGE-1	EGE-1	EGE-1	EGE-1	EGE-1
EGE-2a	EGE-2a	EGE-2a	EGE-2a	EGE-2a
EGE-3	EGE-3	EGE-3	EGE-2b	EGE-5a
EGE-4	EGE-5a		EGE-3	EGE-5c
	EGE-4		EGE-5b	EGE-4
				EGE-5a

Note: Soil type 2a* was determined based on engineering-geological data from a borehole analyzed at a depth of 8.0–10.0 m. This indicates that the engineering-geological characteristics of this soil type are similar to those of the first and second types of foundations in this area.

Fig. 3 Zoning of the territory of Pavlodar by types of the soil bases

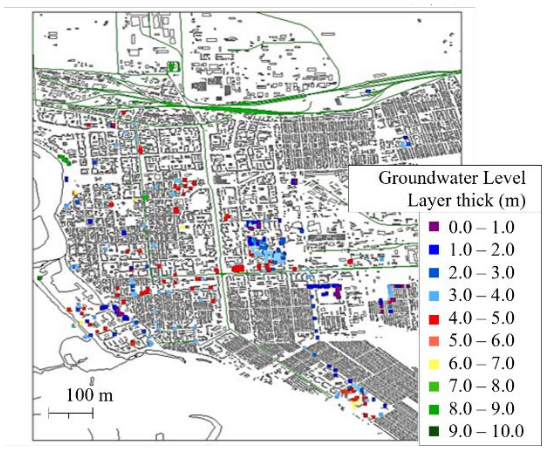


Fig.4 Geotechnical zoning map on the occurrence of groundwater level

4. OPTIMIZING DESIGN SOLUTIONS FOR STRIP FOUNDATIONS BASED ON THE INTERACTION WITH THE SOIL BASE

4.1 The issue of enhancing Design and Technological Solutions in the Realm of Foundation Construction

Based on the results of the study on the interaction between soil bases and strip foundations. In the developed territory of Pavlodar, it was found that strip foundations are the prevailing structural solution. However, an analysis of the physical and mechanical characteristics of the soils revealed that in some cases [16,17], strength and deformation characteristics were incorrectly determined, leading to an overestimation of calculated characteristics. As a result, during foundation design, engineers are forced to provide an unjustified safety margin to avoid non-normative settlements and deformation.

Improvement of structural and technological solutions in the construction of foundations leads to saving material and labor resources and reducing the time of building erection. One of the ways to achieve this goal is to improve the calculation methodology based on changing the geometric dimensions of the footing shape [18]. It has been established that certain sizes and configurations of foundations allow better utilization of the bearing capacity of the soil base and reduce material consumption [19,20]. The design solutions for strip foundations in the Pavlodar region were optimized through a typification process that involved selecting appropriate geometric dimensions for the foundation's base. This typification was carried out using one-, three-, five-, and nine-storey residential buildings with rectangular floor plans and rigid structural systems. The overall dimensions of these buildings were set at 20.2 x 14.2 m.

By calculating the 1 limit state, according to [21], the maximum width of the base of the foundation was determined, and the calculation for the limit state I was carried out. The calculation was performed in several basic stages: a) collection of loads on the foundation; b) collection of permanent and temporary loads; c) determination of the weight of structures; d) determination of the footing area; e) determination of the design resistance of soil; f) calculation of the foundation settlement, performed by the layer-by-layer summation method.

4.2 Optimization of Design Solutions for a Strip Foundation, taking into account the Soil Foundation

In order to optimize the geometric dimensions of the foundation footing on four different soil foundations (Fig. 3), the maximum width of the strip foundation was calculated when laid to a depth of 2.4 m, taking into account the GWL above and below the foundation depth (from 0.5 m to 10.0 m). Engineering-geological conditions at the investigated depth in each type of foundation are represented by a different set of engineering-geological elements (Table 3).

Table 3 Characteristics of the soil bases

Type of soil base	Number of EGE	Thickness, m	Bulk density ρ, g/cm^3	Angle of internal friction ϕ, degree	Cohesion coefficient, kPa
1 type	EGE-2a	0.68-7.96	1.88	29.0	1.21
	EGE-3	7.96-14.7	1.68	34.0	3.00
	EGE-4	14.70-15.66	2.03	32.7	2.00
2 type	EGE-2a	0.90-2.90	1.88	29.0	1.21
	EGE-3	2.90-6.49	1.68	34.0	3.00
	EGE-5a	6.49-11.52	1.97	17.0	106.00
	EGE-4	11.52-15.72	2.03	32.7	2.00
3 type	EGE-2b	3.58-7.91	2.00	16.6	28.00
	EGE-3	7.91-8.84	1.68	34.0	3.00
	EGE-5b	8.84-17.78	1.88	11.0	111.00
4 type	EGE-2a	0.40-3.60	1.88	29.0	1.21
	EGE-5a	3.60-6.05	1.97	17.0	106.00
	EGE-5c	6.50-7.80	2.00	18.0	57.00
	EGE-4	7.80-12.50	2.03	32.7	2.00
	EGE-5a	12.50-20.00	1.97	17.0	106.00

As a result of calculations, the maximum width of the foundation base for one-, three-, five- and nine-storey residential buildings were determined, and the results are presented in Table 4.

The results of this calculation reveal that the base width of a strip foundation varies depending on the type of soil on which the foundation is established, specifically at a depth of 2.4 m. In areas with clay soils (foundations 1, 3, and 4), which have a higher bearing capacity, the foundation base width is significantly greater when the GWL is above the foundation depth, as compared to when the GWL is below. This is due to the better load-bearing capacity of clayey soils and their lower susceptibility to settlement under the influence of water.

Table 4 Maximum width of the sole according to the calculation of the soil strength of the base

Foundation type (type of soil base, EGE, and soil type)	GWL, m	Maximum width of the base of the foundation, m			
		1 st.	3 st.	5 st.	9 st.
1 type, EGE-2a, sandy loam	10.0	0.6	1.2	1.4	2.0
1 type, EGE-2a, sandy loam	0.5	0.8	1.4	1.6	2.4
2 type, EGE-3, fine sands	10.0	0.5	0.9	1.1	1.6
2 type, EGE-3, fine sands	0.5	0.6	1.0	1.4	1.9
3 type, EGE-2b, loam	10.0	0.6	1.4	1.8	2.6
3 type, EGE-2b, loam	0.5	0.8	1.6	1.9	2.8
4 type EGE-2a, sandy loam	10.0	0.6	1.2	1.6	2.4
EGE-2a, sandy loam,4 type	0.5	0.8	1.4	1.8	2.6

Comparing the results of this calculation, it was found that when the GWL is above the depth of the strip foundation, the width of the sole is greater than when the GWL is below the depth of the foundation. In zones with types of bases 1, 3, and 4, the basis for the foundation is clay soils (sandy loam and loam). Under these conditions, the width of the base of the foundation for one-, three-, and five-storey buildings is 33.3% greater at the GWL above the foundation depth than at the GWL below the foundation depth, and for a nine-storey building, it is 20% more. In the zone with the type of base 2, fine sands serve as the basis for the strip foundation, the width of the base of the foundation is 20% more for one- and three-storey buildings, and 27% more for five- and nine-storey buildings.

In the case of fine-grained sandy soils (2 type), which have lower bearing capacity, the width of the foundation base is also greater when the GWL is above the depth of foundation placement. This is necessary to distribute the load over a larger area to ensure the stability of the foundation and reduce the risk of soil settlement.

The difference in the width of the foundation base at different GWL levels can be significant and depends on the height of the building. For single- and three-story buildings, the difference is 20%, while for five- and nine-story buildings, it increases to 27–33.3%. This is because taller buildings impose higher loads on the foundation, requiring a wider base to ensure stability and uniform load distribution on the soil.

These findings underscore the significance of groundwater levels and soil foundation types in foundation design, enabling the optimization of dimensions to ensure the stability and reliability of buildings in line with local soil conditions.

5. RESULTS AND DISCUSSION

The main results of the study can be summarized as follows:

1. Creating a geo-information base, which contains information about the genesis, different types and ages of soils, their physical and mechanical properties, their spatial location, and the position of the base and roof of the engineering and geological elements, is an important scientific task. Such a database allows us to systematize and preserve valuable information about the geological structure and properties of soil formations in a particular region, in this case, the city of Pavlodar.
2. Using the program "Geoinformation Database of Pavlodar" engineers created engineering-geological maps for the geotechnical zoning of the city in accordance with the classification of soils and the criteria of homogeneity of territories. This allowed for the division of the territory of the city into four zones, taking into account the peculiarities of the soils. Geotechnical zoning provides a foundation for informed decision-making regarding land use planning, construction projects, and geotechnical engineering interventions. In addition, a special geotechnical map has been developed to show groundwater levels, which is an important tool in the design of buildings and structures.This map helps prevent problems related to waterlogging, subsidence, and foundation damage, which can

seriously affect the longevity and safety of buildings.

3. Based on the analysis of the physical and mechanical properties of soils in the territory of Pavlodar, the optimization of design solutions for the strip foundation was carried out. The purpose of the optimization was to take into account the interaction of four types of soil bases and to typify the geometric dimensions of the foundation base for one-, three-, five- and nine-storey residential buildings in the area. As a result of the study, the optimal width of the strip foundation footing for each zone was determined, taking into account the groundwater table both above and below the foundation depth.

6. CONCLUSIONS

The analysis of engineering-geological reports and the use of GIS technologies in the program "Geoinformation Database of Pavlodar" are important for the planning and development of urban infrastructure. The determination of criteria for zoning engineering and geological conditions based on these analyses allows you to make informed decisions in the design of engineering structures, monitoring, and examination.

GIS technology and the systematization of data provide valuable information on geotechnical conditions in the territory of Pavlodar. This allows us to divide the territory into zones with different engineering and geological characteristics and apply appropriate approaches in the design and construction of engineering structures.

Thus, the use of GIS technology and the analysis of engineering-geological data contribute to the planning and development of urban infrastructure, taking into account geotechnical conditions, which are the basis for the sustainable and effective development of infrastructure in both megacities and small new-generation cities.

7. ACKNOWLEDGMENTS

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