Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1769

APPLICATION OF GIS TECHNOLOGY IN ENGINEERING-GEOLOGICAL SURVEYS

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ABSTRACT: Today, modern geographic information systems (GIS) are powerful tools in all fields of activity, including in complex engineering and geological surveys, both for scientific and industrial purposes. The results of this work demonstrate the ability of GIS technologies to analyze engineering and geological conditions and to zone building territories by types of bases and foundations in such cities of Kazakhstan as Astana and Pavlodar. GIS technology significantly reduces the time and cost of conducting engineering and geological surveys, designing and building foundations.

KEYWORDS: geoinformation system, technology, engineering-geological surveys, engineering-geological conditions, database.

1 INTRODUCTION

The rapid pace of construction in the country's megacities requires up-to-date information for the justification of design works in construction and for urban development planning. The volume of information available in the modern world is incomparable to that of past centuries. The speed of life is increasing rapidly, and methods of obtaining information are becoming increasingly industrialized. To ensure organized storage, retrieval, processing, and analysis of such data, modern computer-based technologies are required, including the use of geographic information systems (GIS). The application of these technologies enables not only the visualization of existing data in the form of maps and various property fields, but also the analysis of data, modeling of geological fields in time and space, and prompt acquisition of new information on demand. Furthermore, it allows for assessment of geosystem conditions and forecasting of its development [Demidenko, 2008].

The development of geological environment geographic information systems (GIS) within engineering geology is one of the pressing tasks of the current century. This is due to the fact that one of the most important objectives of engineering and geological investigations is to predict potential changes in the interaction between a planned structure and the geological environment. These studies become significantly more complicated in the absence of detailed descriptions and established patterns of variation in the composition and properties of specific lithological-genetic types and soil complexes. For effective forecasting of the geological environment in the construction sector, it is advisable to use GIS technologies that take into account many years of construction experience within the city.

2 CURRENT STATE OF GIS DEVELOPMENT IN ENGINEERING-GEOLOGICAL STUDIES ABROAD

The development of Geographic Information Systems (GIS) in engineering and geological investigations has been ongoing since the early 20th century.

For instance, the archive of the Helsinki Geotechnical Department (Finland) contains data from 20,000 boreholes (dating back to 1903), which have been used to create maps of Quaternary deposits, bedrock, and the foundations of old structures in the city of Helsinki.

In Japan, special attention is paid to the use of specialized engineering-geological maps during the design of structures. These maps are based on systematically collected data from engineering-geological investigations, a practice that has been in place since the 1950s. For example, the Kansai Prefecture geoinformation database, developed in 1966, currently includes more than 40,000 boreholes [Geo-Research Institute, 2005].

Since the 1960s, the Czech Republic has been developing special geotechnical maps alongside engineering-geological maps. These maps correspond to various stages of construction and include data on soil properties, filtration characteristics, strength, and other relevant parameters.

In 1966, Harvard University's Computer Graphics Laboratory (USA) introduced the SYMAP cartographic system, which was implemented in the state of Minnesota. This system laid the foundation for all modern GIS platforms. It stood out for several features, most importantly — it was one of the first fully completed and successfully implemented systems, proving its efficiency. Today, GIS is widely used throughout the United States, not only in engineering and geological surveys but also across various other sectors.

In Sweden, since the 1980s, engineering-geological mapping has been conducted to assess the suitability of land for construction and to perform indirect economic evaluations. The availability of large-scale engineering-geological zoning maps for the central part of Stockholm has made it possible to develop a structural foundation map of historic buildings, propose measures for their strengthening and renovation, and design a standard method for calculating zero-cycle construction works for new standard buildings.

In Russia, the creation of GIS is also considered a highly relevant topic. For example, under the mandate of the federal district, the city of Perm developed a program titled "Information System for Engineering and Geological Surveys in Urban Development" during 2010–2012. The goal of the program was to create a comprehensive information system that would provide individuals and organizations with reliable data necessary for cost-effective construction [Konoplev et al. 2012].

3 KEY CRITERIA FOR DEVELOPING GIS FOR ENGINEERING-GEOLOGICAL SURVEYS

The use of GIS enables prompt access to requested information and its display on a cartographic base, as well as the assessment of the geosystem's condition and the forecasting of its development.

Capabilities of GIS applicable to engineering-geological investigations include:

- input, accumulation, storage, and processing of digital cartographic and geotechnical information;
- creation of thematic maps based on the collected data, reflecting the current state of the geosystem;
- study of the dynamics of geotechnical conditions over time and space;
- generation of graphs, tables, and diagrams;
- modeling of geotechnical developments under various environments and investigation of the relationship between the geosystem state and engineering-geological conditions, foundation characteristics, and construction objects;
- obtaining comprehensive assessments of construction sites based on heterogeneous data.

Geotechnical issues often require immediate and appropriate actions, the effectiveness of which is directly linked to the speed and quality of information processing and presentation. Due to the multidisciplinary nature of engineering-geological surveys, there is usually a need to rely on generalized parameters related to design and construction. As a result, even the minimum sufficient amount of baseline data must be large. Without this, it is unlikely that informed and justified decisions can be made. However, simply accumulating data is not enough. The data must be readily accessible and systematized in accordance with specific needs.

Ideally, it should be possible to link heterogeneous data, compare and analyze them, and view them in a convenient and visual format—such as through a generated table, diagram, blueprint, or map. The grouping of data, its proper visualization, comparison, and interpretation fully depend on the researcher's qualification, expertise, and approach to interpreting the accumulated information. At the stage of data processing and analysis, technical support plays an important, though not the primary, role. This includes appropriate hardware and software for solving the given tasks.

This highlights the need to develop a problem-oriented software complex for solving zoning tasks in engineering geodynamics. Such a system should include a module for modeling engineering-geological conditions of areas with specified properties and known parameters for determining the geological structure characteristics. This would allow the division of a territory into zones that differ based on generalized characteristics.

A comprehensive GIS should include four main components: data input (tabular data entry, cartographic material scanning, remote sensing methods); data storage, quick access, and updating; processing and modeling of geological parameter fields; data presentation (maps, tables, or reports).

The use of these technologies enables not only the representation of existing data in the form of maps and various property fields, but also the analysis of this data, the modeling of geological fields in both time and space, and the acquisition of new information.

Therefore, the development of the necessary software in a machine-oriented environment can be viewed as a step-by-step formation of a hierarchy of mathematical and informational models. This hierarchy may include: the Engineering-Geological Model (EGM), the Geotechnical Model (GTM), and the Geological-Urban Planning Model (GUPM).

Each of these models represents a combination of data sets (databases) and methodological and software tools.

The structure of the EGM database includes the following data sets:

- results of engineering-geological surveys conducted in the construction area (data obtained during investigations and subsequent processing);
- data on types and structural characteristics of buildings planned for construction in the area;
- datasets containing information on averaged engineering-geological strata within zones of conditionally homogeneous conditions identified in the area;
- and other necessary information.

The methodological and software components of the EGM include tools for generating and processing the data sets stored in the EGM database. The construction of the EGM primarily involves assembling a comprehensive dataset of engineering-geological investigations of the planned construction site.

The next model, GTM, is based on the data sets from the EGM and is used to evaluate the territory. GTM construction involves dividing the territory into zones with conditionally homogeneous engineering-geological conditions and generating data sets with averaged engineering-geological strata for each identified zone. This allows for the creation of engineering-geological typification maps by foundation type, as well as maps of Quaternary deposits and bedrock.

The development of the GUPM is based on the sequential construction of the EGM and GTM. The first step in developing the GTM is to perform multivariable foundation calculations for the construction of specified building types in each conditionally homogeneous zone. These calculations are based on the data stored in the averaged strata datasets. Based on the results of these calculations, the GUPM includes the creation of special geotechnical maps for the construction area, such as maps for optimizing pile lengths, maps of recommended building height distribution, and others. These are typically based on criteria such as pile bearing capacity.

The methodological and software infrastructure of the GUPM includes tools for performing multivariable calculations and tools for generating geotechnical maps. Thus, based on the special geotechnical maps included in the GTM, optimal foundation types can be selected for development areas, taking into account subsurface conditions and previous construction experience on similar soil types.

Therefore, promising approaches include the use of calculation methods based on empirical dependencies derived from real observations of ongoing and completed construction projects. Such dependencies can be obtained through statistical analysis of databases containing long-term and reliable observations, as well as engineering-geological information on foundation soils of the studied structures.

As a result of this modeling approach, designers receive sufficiently accurate quantitative information for evaluating the engineering-geological conditions and for the preliminary selection of foundation types suitable for the area under study.

After the final planning design is approved, if necessary, additional engineering-geological investigations may be conducted to precisely determine the subsurface layers beneath each planned structure. Subsequently, a revised multivariable calculation is performed to select the optimal solution [Alibekova, 2009].

3.1 MATERIALS AND METHODS

3.2 *Data Inventory and Sources*

For the assessment of engineering-geological conditions in the urban areas of Astana and Pavlodar, a unified geoinformation database was created in collaboration with Japanese geotechnical specialists [Mimura and Yamomoto, 2012]. In Astana, the "Geoinformation Database" was compiled using materials from 87 investigated sites and currently includes data from 1200 boreholes, 402 static penetration points, and 125 dynamic tests. In Pavlodar, a similar program was developed incorporating 558 boreholes across more than 80 sites investigated from 2014 to 2022, with information on physical and mechanical soil properties obtained from 2249 soil samples taken from the surface down to 25.0 m depth [SP RK 1.02-102-2014, SP RK 1.02-105-2014].

3.3 *Geographic Information System for the City of Astana*

The city of Astana has served as the capital of the Republic of Kazakhstan since December 10, 1997.

In 2008, a program titled "Geoinformation Database of Astana" (see Fig. 1) was developed for the first time to support the assessment of engineering-geological investigations in the city. This system made it possible to analyze regional soil conditions even before conducting detailed site-specific studies. Following the methodology described by [Zhussupbekov et al. 2021], the geoinformation database of Astana allows the identification of six main engineering-geological elements (EGE) within the city and provides comprehensive information on key soil properties, including bulk density, moisture content, and deformation modulus (see Fig. 2). The bulk density distribution of eluvial soils corresponds closely to moisture content, generally ranging from 1.8 to 2.2 g/cm³. The deformation modulus E was determined through plate load tests conducted during site investigations and static load tests for driven piles during construction. Eluvial soils exhibit higher E values, typically between 7 and 20 MPa, whereas most alluvial soils vary from 3 to 12 MPa, reflecting the greater strength and consolidation of eluvial soils compared to the unconsolidated or redeposited alluvial sediments. Analysis of these datasets enabled the classification of soil layers into taxonomic mapping units, the assessment of soil behavior under structural loads, and the division of the built-up area of Astana into conditionally homogeneous geotechnical zones according to foundation type. The geoinformation database thus supports optimized design and construction planning, allowing for the rational selection of foundation types, evaluation of soil bearing capacity, and mitigation of engineering risks in urban development [SN RK 2.03-01-2011].

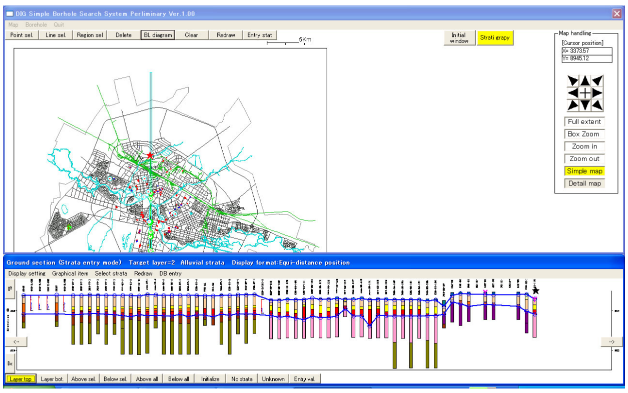


Figure 1. General view of the "Geoinformation Database of Astana" program

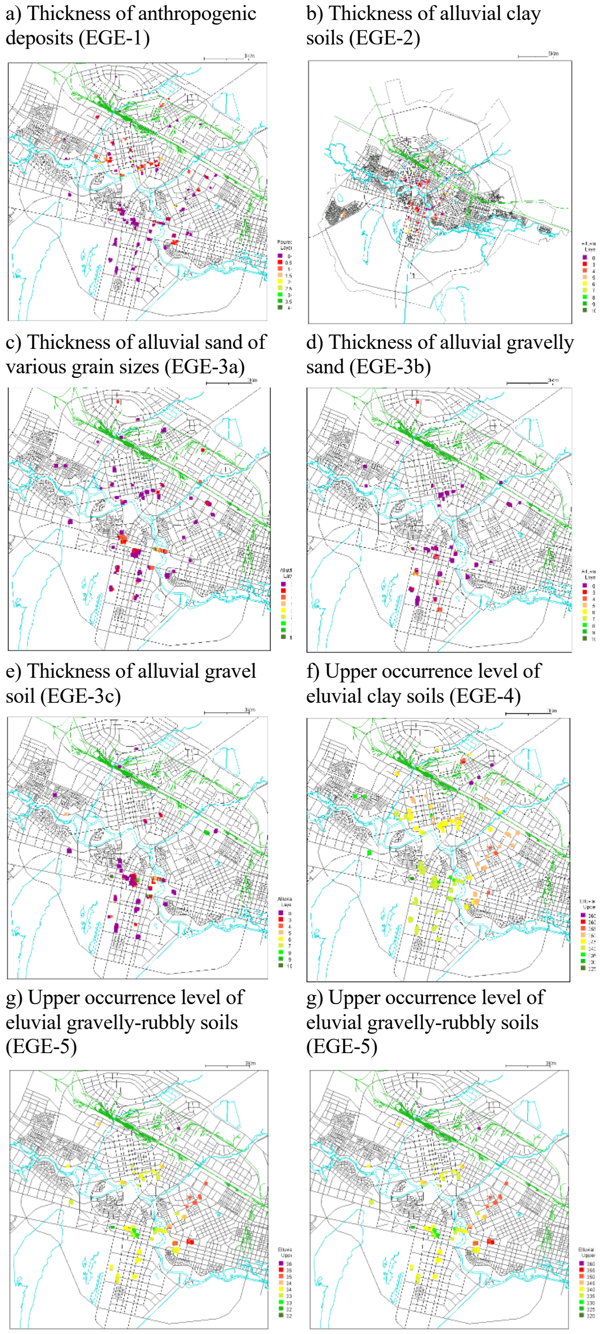


Figure 2. Engineering-geological maps of the city of Nur-Sultan

In addition, using the "Geoinformation Database of Astana" program, special geotechnical zoning maps were developed. These include zoning by foundation types and optimization of driven pile lengths for buildings with a normal (Level 2) responsibility level, taking into account the foundation type (see Fig. 3) [Zhussupbekov et al. 2012].

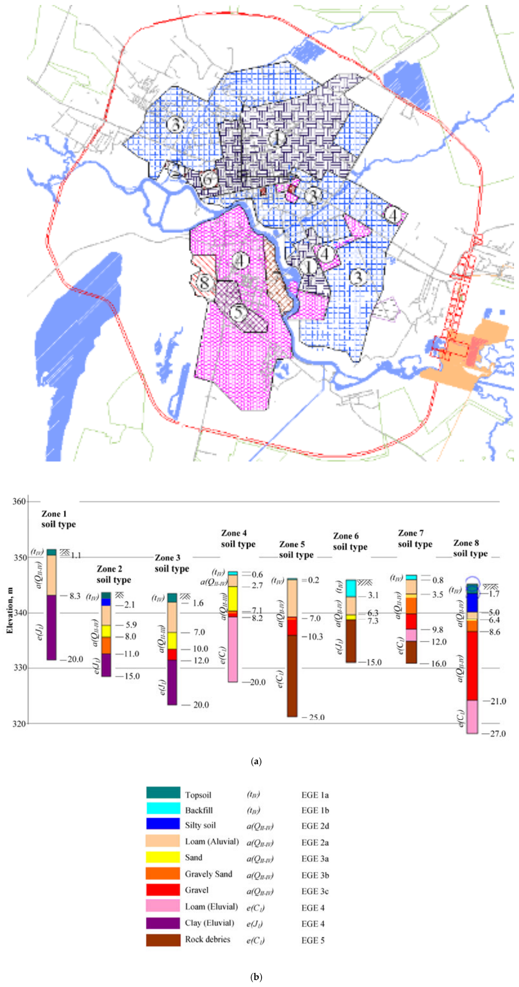


Figure 3. Geotechnical zoning map by foundation types

3.4 *Geographic Information System for the City of Pavlodar*

The city of Pavlodar is a center of industrial and cultural development in the Republic of Kazakhstan. It is located in northeastern Kazakhstan, approximately 450 km northeast of the nation's capital, Astana, and 405 km southeast of the Russian city of Omsk, situated on the Irtysh River.

In 2022, a program titled "Geoinformation Database of Pavlodar" (see Fig. 4) was developed for the first time to assess engineering-geological investigations in the city. This program also enabled analysis of regional soil conditions prior to detailed site-specific studies.

The territory of Pavlodar is underlain by six main engineering-geological elements (EGE), varying in origin and age (see Fig. 5) [Alibekova et.al, 2023].

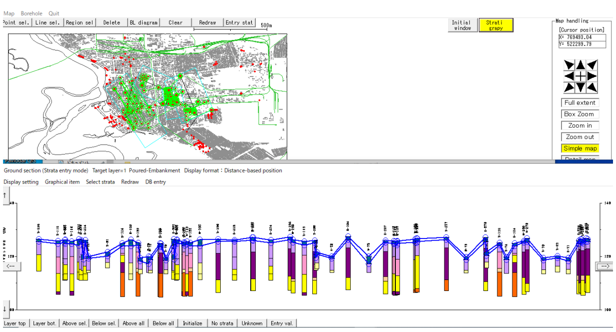
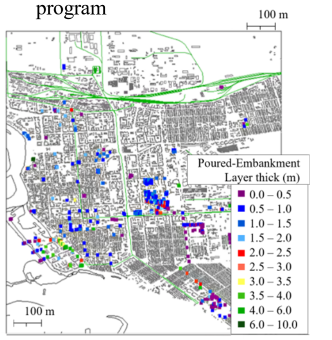
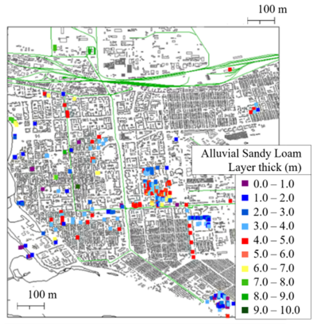


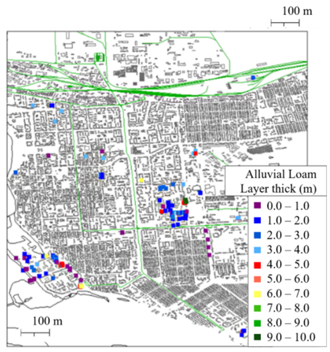
Figure 4. General view of the "Geoinformation Database of Pavlodar" program



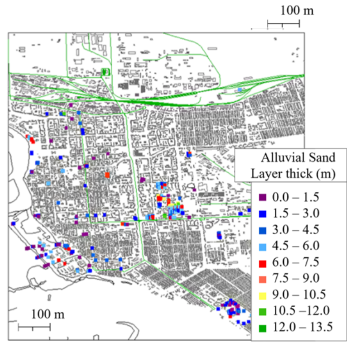
a) Thickness of anthropogenic deposits



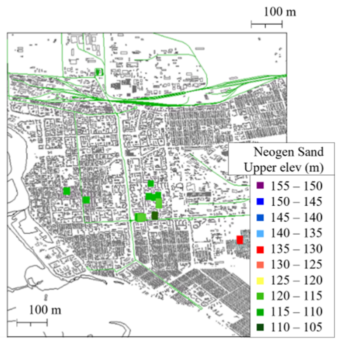
b) Thickness of alluvial-deluvial sandy loam soils



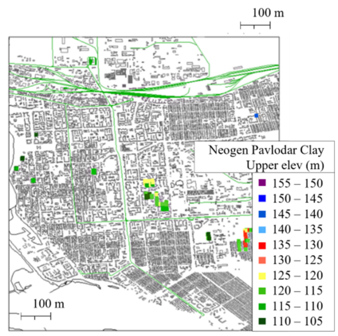
c) Thickness of alluvial-deluvial loam soils



d) Thickness of alluvial-deluvial sands



e) Upper occurrence level of Neogene-age sands



f) Upper occurrence level of Neogene-age clay soils of the Pavlodar Suite

Figure 5. Special geotechnical maps for soil classification in the city of Pavlodar

The engineering-geological conditions were typified by conducting construction zoning based on the number of floors of residential buildings, as shown in Fig.61. 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.

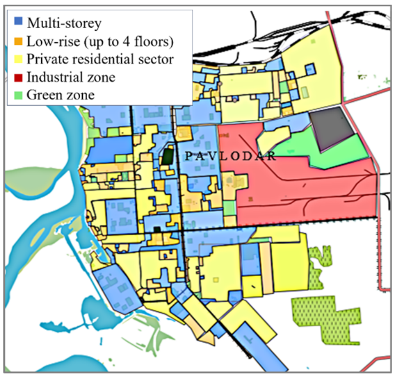


Figure 6. Scheme of construction zoning of Pavlodar

4 PROSPECTS FOR THE USE OF GIS IN THE REPUBLIC OF KAZAKHSTAN

The development of GIS and its implementation in engineering-geological investigations in Kazakhstan will help optimize engineering-geological activities, eliminate duplication of work on the same sites, and ensure prompt access to essential information for justifying design decisions in construction and for urban development planning (see Table 1).

Table 1. Comparative analysis of the type and duration of engineering-geological surveys at the feasibility study (FS) stage using standard methods and GIS technology.

	Drilling of boreholes	Field tests	Laboratory work	Technical report	Execution time
Standard method (without GIS technology)	+	+	+	+	minimum of 30 days
GIS technology	-	-	-	+	1 day

Moreover, this GIS makes it possible to develop engineering-geotechnical maps for the geotechnical zoning of urban areas based on soil classification and homogeneity criteria of the formed zones, as well as for optimizing foundation dimensions depending on soil properties. It also helps determine possible foundation types, soil bearing capacities, and adopt appropriate structural solutions.

However, the dynamic expansion of the geoinformation database and engineering-geological maps grows only with the continuous influx of new data. Therefore, a prerequisite for the systematic and effective resolution of various engineering-geological issues related to the construction and operation of urban infrastructure - as well as for the ongoing monitoring and analysis of the geological environment — is the establishment of a dedicated geo-service within governmental bodies of large cities.

This geo-service would be responsible for collecting and processing materials from engineering-geological investigations carried out within the city. It would prevent duplication of work, unlock the potential of unused archival data, ensure a rational approach to the scope and scale of investigations, and ultimately contribute to reducing costs and timelines while improving the overall quality of studies.

As such, prior to commencing work, the contractor or client should request information regarding the availability of engineering-geological investigation data for the proposed construction site. Then, together with the geo-service, the contractor (or client) determines the composition and scope of required works based on the existing data.

In conclusion, GIS should become a vital tool for local authorities and businesses in regional planning. The costs of implementing GIS are recouped in the shortest possible time.

5 CONCLUSIONS

The implementation and use of GIS technologies in engineering and geological surveys contribute to the sustainable development of megacities, providing models and approaches for the urban development of geoinfrastructure in next-generation large and small cities.

The economic efficiency of applying GIS and the development of engineering-geotechnical maps significantly reduces the time and cost of conducting surveys and design works, as well as the construction of building foundations in complex soil conditions.

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