






Preliminary Assessment of the Bearing Capacity of Soils Using a Geotechnical Database

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Abstract. Geotechnical survey are an important part in design of building and structures. The geological data from 3500 boreholes and 1927 in-situ testing were collected into a unified Geotechnical database of Nur-Sultan, Kazakhstan. The city territory was regrouped into 8 zones, based on the geological origin and stratigraphy interposition of the six main engineering-geological elements (EGE). The developed geotechnical database was improved with the results of previously conducted Static Load Testing (SLT) and Pile Dynamic tests (PDA). A preliminary assessment of the pile length for each zone of the city was determined, corresponding to the geological structure and survey data from the previous and ongoing geological reports. The improved geotechnical database allow a preliminary assessment of the bearing capacity of soils, the optimal parameters of the pile length, labor costs and financial costs for the construction of foundations at the design stage.

Keywords: Geotechnical database · Pile length assessment · Bearing capacity of soils · Geological survey · Geotechnical survey

1 Introduction

1.1 Study Background

Access to materials on previously performed engineering surveys in Kazakhstan during the Soviet era was provided by huge state organizations, such as the Kazakh Research Geological Institute (KazGIIZ). KazGIIZ had its own regional expeditions, departments, branches in all regions of the country and was responsible for the unified technical policy in the field of engineering surveys for all types of construction [1–3]. In 1985–1991 restructuring took place and the established system of collecting, storing and providing materials for engineering surveys was destroyed, mainly due to the lack of a local research trust in the field of construction. The archive of previously collected geological research and the sharing system was destroyed. Some of them were lost, and some were transferred to private companies that did not want to share information in commercial interests. According to Popov [4], insufficient information about the soil, the wrong choice of the type of piles, their length and horizontal dimensions, as well as the failure to use

the maximum bearing capacity of the foundation at the required level, often led to the destruction of structures or excessive consumption of construction materials. In 1997, due to the movement of the new capital of Kazakhstan to Nur-Sultan city, an intensive construction began in the city [5]. At the same time, it became necessary to create a unified geotechnical database where the compositions of the basement soils and their engineering properties would be predetermined [6–9]. The work on collecting material and creating such a map began in 2007 by N. Alibekova, under the supervision of A. Zhussupbekov, and by 2018 the city was conditionally divided into subzones with an identical sequence of location of engineering geological elements (EGE) [10, 11]. Further development of construction in the capital required the development of more specialized and detailed map, or a database contacting the information regarding the bearing capacity of soils for a preliminary assessment of foundation at different part of the city, in particular to estimate the labor and financial costs of the designed projects.

2 Methods

2.1 Geotechnical Zoning of Nur-Sultan City

Using the “Geotechnical Database” program, all the existing data of engineering and geological surveys to this day, including existing boreholes data, were digitalized and formed the unified system. In Fig. 1, the city was split into 8 zones with the highlighting of their hatching, which means the identity of the soil layers a certain sequence [12]. Assessment criteria for the EGE classification were:

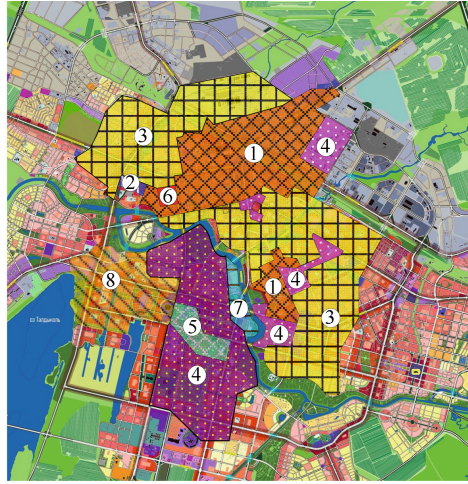
- physical-geographical, geological, geomorphological and lithological conditions;
- qualitative and quantitative characteristics of the structure, composition, condition of soils; their genetic, age and petrographic properties and mapping of the variability of their indicators;
- physical properties of the soils, such as particle size analysis, plasticity limits, dry density, moisture content in the natural conditions,
- mechanical properties, such as deformation modulus, cohesion and angle of internal friction.

Knowledge of age and petrographic types of soils made it possible to assess the conditions of soil occurrence. While physical and mechanical characteristics allows assessing the suitability of soil for the foundation of buildings and structures.

Six basic geotechnical elements (EGE) were determined after analyzing the physical and mechanical properties of soils that form the basis of urban foundations. The thickness and strength of soils, as well as the modulus of deformation are presented in Table 1.

EGE-1 consists of technogenic deposits (t_{IV}) represented by the topsoil (EGE-1a) and backfill layers (EGE-1b). The topsoil mainly comprise sandy clays, silty clays and sandy silty clays, waste soils with low density and bearing capacity properties. The thickness of EGE-1 varies from 0.2 to 2.0 m.

EGE-2 represents alluvial mid-Quaternary modern deposits ($a(Q_{II-IV})$) with a thickness of 0.9 to 10.0 m, consisting of sandy and silty clays (EGE-2a) with interlayering



1 soil type	2 soil type	3 soil type	4 soil type	5 soil type	6 soil type	7 soil type	8 soil type
EGE-1	EGE-1	EGE-1	EGE-1	EGE-1	EGE-1	EGE-1	EGE-1
EGE-2a	EGE-2d	EGE-2a	EGE-2a	EGE-2a	EGE-2a	EGE-2a	EGE-2d
EGE-4	EGE-2a	EGE-3a	EGE-3a	EGE-3b	EGE-2b	EGE-2b	EGE-2a
	EGE-4	EGE-4	EGE-3b	EGE-3c	EGE-4	EGE-3a	EGE-3a
			EGE-3c	EGE-5		EGE-3b	EGE-3b
			EGE-4			EGE-3c	EGE-3c
						EGE-4	EGE-4

Fig. 1. Geotechnical zoning of Nur-Sultan city by the soil types.

silty clayey sands and sandy silty clays (EGE-2b), clays (EGE-2c) and silty soils (EGE – 2d). Over the entire thickness, there are lenses and inter layers of sands of various sizes up to 1–3 cm, sometimes up to 10 cm. EGE-2 is a part of weak water-saturated soils stratum, distributed over the city in a medium plastic, highly plastic and liquid state, which is considered as a highly compressible soil base.

According to the survey materials, all sandy-gravel soils are similar in color, clay lenses are slightly present and differ only in the amount of the determining fraction. These deposits are horizontally stratified.

EGE-3 consists of sands of various sizes (EGE-3a), gravelly sands (EGE-3b) and gravel soils (EGE-3c), belonging to alluvial medium-Quaternary sand and gravel formations $a(Q_{II-IV})$. The depth of occurrence is 2.5–8.0 m. The thickness of sands of various sizes ranges from 0.4 to 6.3 m, gravelly sands from 0.5 to 6.5 m, gravel soils from 1.0 to 9.2 m. According to the survey materials, all sandy-gravel soils are similar in color; clay lenses are occasionally present and differ only for fraction amount. These deposits are horizontally stratified.

EGE-4 is an eluvial formation of the weathering crust $e(C_1)$ which presented with sandy clays and silty clays. EGE-4 located beneath the sand and gravel alluvial formations at a depth of 6.0–10.0 m. Gray, greenish-gray and yellowish-gray clays and silty clays, in composition ferruginous, manganese with the inclusion of coarse-grained fractions up to 25%, and in some lenses up to 40%.

EGE-5 are gravel-gruss-rubble soils of eluvial formations of the weathering crust $e(C_1)$ widespread on the site and found at a depth of 7.0 to 23.0 m. The thickness of the layer of occurrence of rubble-gravel soils is from 1.7 to 9.0 m. The particle size analysis shows that grit-crushed gruss and rubble soils represented by a fraction of more than 2.0 mm in size range from 81.3 to 98.5% with an average value 92.3%. The bulk density of this soil layer is around 2.14 g/cm³.

Table 1. Engineering geological stratification.

Engineering-geological element (EGE)	Geological index (age)	Soil subtype	Limits of change in layer thickness, m	Deformation Modulus (Young's Modulus) E, MPa
EGE--1	t_{IV}	EGE--1a	0.3–1.4	
EGE--2	$a(Q_{II-IV})$	EGE--2a	1.7–4.4	4.3
		EGE-2b	0.3–0.7	4.3
EGE--3	$a(Q_{II-IV})$	EGE--3b	1.3–3.5	21.2
		EGE-3c	2.8–5.2	> 30
EGE--4	$e(C_1)$	EGE--4	2.2–3.3	10.75
EGE--5	$e(C_1)$	EGE--5	> 4	> 30
EGE--6	(C_1)	EGE--6	3.3–23.0	

EGE-6 is composed of sedimentary rocks of the Lower Carboniferous (C1), which mainly represented by sandstones, interbedded with siltstones and mudstones of the same age throughout their entire thickness. EGE-6 layered at a depth of 11.6 to 26.2 m, the thickness of which varies from 3.8 to 23.0 m. Sandstones, siltstones are gray, dark gray and greenish gray in color, fractured in texture, composition ferruginous and manganese, weathered.

In Fig. 2, using the Geotechnical Database program, geotechnical sections were built as an example of the location and thickness of layers in each zone of the Geotechnical Map. The thickness of the soil layers can vary and therefore the EGEs provided are representative examples of the location of the layers in the soil column from boreholes located in each zone.

On the example of Fig. 2b, zone 1 is represented by 3 layers. The 1st topsoil layer (EGE-1a) has 1.1 m thickness and ranked as a weak soil with low density parameters for construction. Below are sandy and silty clays $a(Q_{II-IV})$, designated as IGE-2a, physical and mechanical characteristics of this layer are presented in Table 2. Load-bearing soils are eluvial layer of sandy clay $e(J1)$ (EGE-4). With the help of Geotechnical Database

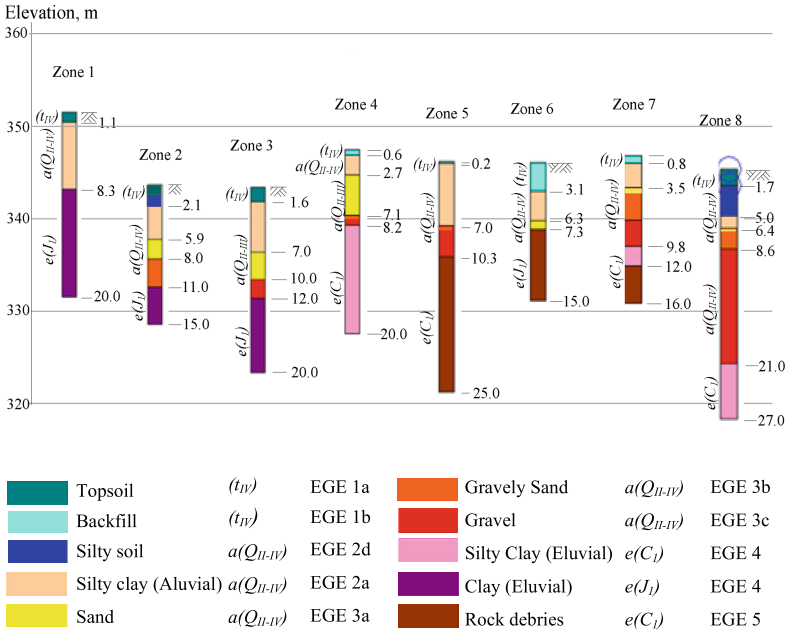


Fig. 2. Vertical profiles of boreholes for each type of soil zones with decoding.

program, it was possible to build up the conditions for the settlement and the soils stratigraphy in any part of the city (Fig. 3).

2.2 Development of a Special Geotechnical Zoning Map for the Optimal Pile Length

Because silty clays and clayey soils comprise the soil base of the capital to a depth of 8–16 m, then deep foundations are the main type of foundations for residential, administrative and industrial buildings and structures in Nur-Sultan city.

The bearing capacity of piles in different soil zones was determined by Dynamic Load Testing (PDA) and Static Load Testing (SLT) according to Standard SP RK 5.01–103-2013 (2013). The tests carried out on the bearing capacity of piles in various zones of the city, the results of which were collected and digitalized into a single database, taking into account field observations under similar engineering and geological conditions. In PDA pile driving was carried out with an NNK-5A hydraulic hammer with a shock mass of 5.0 tons and a headband of 0.65 tons. Pile penetration resistance during their driving ranged from 0.83 to 1.67 cm. Final stage of the driving was carried out with a hydraulic hammer NNK-7A with a mass of the impact part of 7.0 tons and a headgear of 0.80 tons, with two consecutive series of three and five blows after 19 days from the end of pile driving. The bearing capacity of the piles was determined on the basis of statistical processing of the test results of piles in accordance with GOST 20522–96. The SLT of the driven piles were carried out with the addition of a load of 60 kN for each step until the stabilization at each stage, i.e. until the settlement per hour did not exceed 0.1 mm.

Table 2. Soil characteristics of the layers in zone 1.

Physical and mechanical characteristics	Silty clays $a(Q_{II-IV})^*$ (EGE-2a)	Silty clays $e(J_1)$ (EGE-4)
Moisture content W , %	19.1 (10.2–27.7)	24.1 (11.7–37.4)
Liquid Limit W_L , %	30.0 (21.0–48.0)	39.0 (28.0–58.0)
Plastic Limit W_P , %	18.0 (14.0–32.0)	27.0 (20.0–38.0)
Plastic index PI , %	12.0 (7.0–16.0)	22.0 (8.0–30.0)
Liquid index, LI	0.39 (<0–1.0)	< 0
Particle density ρ_s , r/cm^3	2.71 (2.67–2.74)	2.74 (2.71–2.78)
Bulk density ρ , r/cm^3	1.98 (1.84–2.09)	1.96 (1.90–2.12)
Void ratio e	0.63 (0.50–0.68)	0.70 (0.59–0.80)
Degree of saturation S	0.74 (0.50–1.11)	0.96 (0.81–1.08)
Cohesion c , kPa	15	27
Angle of internal friction ϕ , degree	22	29
Elasticity modulus E , MPa	7	10

* The first number is a value for the presented borehole, the maximum and minimum values are in brackets.

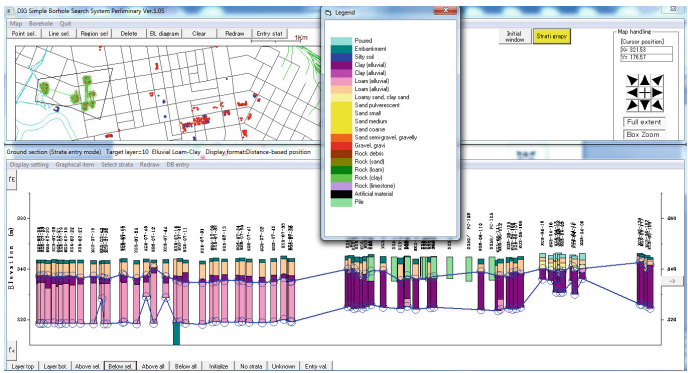


Fig. 3. Obtaining a geologic cross section by the designated points.

The maximum applied load was 680 kN. The unloading took place first by 120 kN every 15 min for three steps, then by 180kN and 240 kN at the end.

3 Results

The bearing capacity of the driven pile based on the SLT and PDA test results were collected together for each zone of the city according to Fig. 1. This takes into account the variation of the data within the upper and lower limits of the data presented in Table 3.

With the help of the Geoinformation Database program, contour maps of optimal pile lengths were built. This made it possible to build a map of engineering-geological zoning to optimize the lengths of driven piles for buildings of a standard level of responsibility, taking into account the type of foundation (Fig. 4). The previously performed full-scale test results were recorded in the geotechnical database and taken as a basis for creating an optimization map for the length of piles in various zones of the city.

According to driven pile length map in Fig. 4, the piles were driven to the required depth within 8.5; 9.0; 9.5m in zones 1 and 2. The supports firmly rest on its low ends, soil layers with high density. In zone 3, the length of the driven piles reduced to 7.5; 8.0; 8.5m because of underlying gravelly soils. In zone 4, there is a sufficiently reliable sand layer above the gravelly soils. Therefore, the length of the driven pile is reduced to 5.1; 5.6; 6.3m at such stratigraphy points. In other places, due to the lower occurrence of soils with sufficient bearing capacity, the designed length of the driven piles extended up to 11.5 m and lower. In zone 5 in some places underlying gravelly soil lenses provide a good support at 6.5 m depth. Following geographical location the entire Left Bank of the Esil River is located in zones 4 and 5. The optimum pile length for zone 6 is 8.5 m, although it is possible that Fig. 5 represents the best borehole in terms of engineering and geological stratification for zone 6 here. Notably the stratification and the placement of rock debris layers change with depth varies as it approaches the Esil River.



Fig. 4. Zoning map for optimization of pile length.

Zone 7 includes the alluvial compositions of soils and is mainly reserved for parks and green zones. Several reinforced engineering structures with additional soil stabilization measures allocated there with bridges and overpasses. There are also state construction sites, the house of ministries, in this regard; obtaining detailed data on the depth of the piles was difficult. In zone 8, the famous architectural complex Khan-Shatyr is located, as well as residential quarters under construction in Zhagalau. This area is complicated by frequent seasonal floods, but due to rehabilitation procedures, it has been additionally drained. The soils are represented by silty soils, interbeds of alluvial silty clays above gravelly layers. The optimal pile length for zone 8 is from 10.3 m and below, depending on the results of field surveys at the site.

Table 3. Bearing capacity of the driven piles according to the performed tests.

Soil type	Pile depth variation within each zone, m	Bearing capacity of the driven piles, kN			
		Based on test results (maximum and minimum values), kN	Calculated according to SP RK 5.01–103-2013 (2013). (upper and lower reading limits)		
			Under the lower end of the pile	Frictional resistance of the pile	Total bearing capacity
Zone 1	8.5–9.5	1026.0–1270.0	450.0–977.0	0–465.0	882.4–1054.2
Zone 2	8.5–9.5	660.0–846.0	360.0–439.5	360.0–439.5	498.7–710.0
Zone 3	7.0–8.5	673.0–746.0	326.3–873.0	121.1–324.4	454.1–1197.4
Zone 4	6.0–11.5	705.0–1192.0	369.5–466.2	395.5–463.3	865.3–1039.2
Zone 5	5.7–8.5	490.0–975.0	434.7–900.0	0–129.5	434.7–949.8
Zone 6	8.5–8.6	606.0–938.0	362.7–643.5	186.5–438.1	555.9–898.9
Zone 7	7.3–8.0	637.0–1020.0	875.7–885.5	0	875.7–885.5
Zone 8	10.3–11.5	533.0–910.0	432.0–460.8	0–457.1	432.0–944.8

4 Discussion

Based on the analysis of the physical and mechanical characteristics of soils, the territory of the city of Nur-Sultan was divided into eight zones with an identical set of EGE. Zones 4, 7 and 8 involve various types of alluvial soils according to geological surveys of stratigraphic dependence, and therefore are the most difficult in terms of designing buildings and structures on them. Geographically, these zones are located on the Left Bank of the Ishim River and are the foundations for a new city with significant attractions, a business center, extensive park areas and a residential area, the development of which is still ongoing.

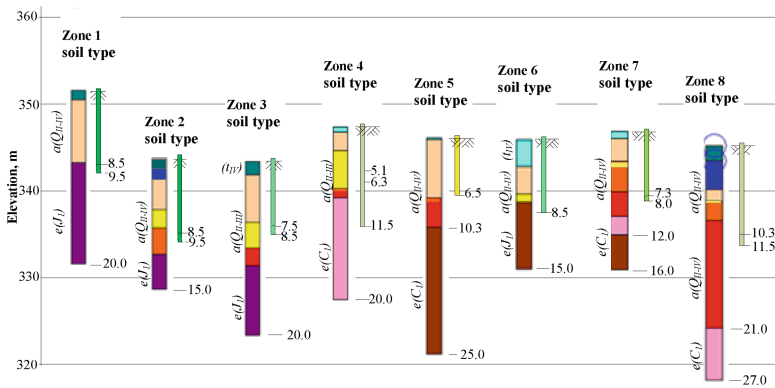


Fig. 5. The representative borehole profiles and a pile length for each city zone.

And on the territory of the old city, on the right bank of the Ishim River, there are zones 3 and 1, there is a lack of engineering-geological element 3, representing alluvial mid-Quaternary sand and gravel formations a(QII-IV).

The optimal pile length varies from 6–8 m on the reliable soil zones of the city to 12 m near the Ishim River, occasionally reaching 16 m of the pile length to ensure the bearing capacity in areas with a large thickness of alluvial soils. On the right bank of the Ishim River (the upper side of the city in Fig. 2), near the railway line of the old town, there are soils with shallow bedding of eluvial layers. Wetlands and a high level of groundwater in zone 8 in the lower left part of Fig. 2 justify the increased pile depth of up to 16 m or more in swampy areas. The high thickness of alluvial soils, considered a weak base, compared to deeply buried eluvial soils, contributes to an increase in the length of piles to be driven.

5 Conclusions

Based on the results of the study, the following conclusions were highlighted:

1. The territory of the city of Nur-Sultan was regrouped into 8 zones, based on the geological origin and stratigraphy interposition of the six main engineering-geological elements (EGE).
2. Depending on the type of underlying soil layers, a zoning map was improved to estimate the bearing capacity of the soils, based on the results of previous SLT and PDA tests recorded in the geotechnical database.
3. A preliminary assessment of the pile length for each zone of the city was determined, corresponding to the geological structure and survey data from the previous and ongoing geological reports.
4. The improved geotechnical database allows a preliminary assessment of the bearing capacity of soils, the optimal parameters of the pile length, labor costs and financial costs for the construction of foundations at the de-sign stage.

The information provided in the Geotechnical Database is necessary for construction organizations for a preliminary assessment of the cost of projects and the timing of work when submitting applications and participating in tenders. The preliminary determination of the bearing capacity of the soils is also important for the selection of equipment and testing technique for the in-situ tests.

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