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FEATURES OF TESTING PILES FOR HIGH-RISE BUILDINGS IN DIFFICULT SOIL CONDITIONS IN ASTANA

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ABSTRACT: The project consists of a high-rise building supported on boring and driven piles. An assessment was made of the current practice in the foundation design of high-rise buildings in Astana, Kazakhstan, to explore areas for improvement. Pile testing is usually undertaken to provide relevant information on one or more of the following issues: the ultimate load capacity of a single pile, the load-settlement behavior of a pile, the acceptability of the performance of a pile, and the structural integrity of a pile. A three-stage process of foundation design and verification will be described, and the importance of proper ground characterization and assessment of geotechnical parameters will be emphasized. According to the test results, the bearing capacity of driven and bored piles was determined, and a comparative analysis was carried out according to the results of tests for cone penetration (CPT). The analysis of the obtained results showed that the dynamic DLT method (according to GOST) compared with static SLT (according to GOST) and cone-penetrating tests (CPT, according to GOST) showed a low bearing capacity of about 30-40 percent. According to comparative analyzes, the static testing method of piles was determined to differ from the CPT by about 15 percent. These investigations are important for the understanding of soil-structure interaction, especially of boring and driven piles in construction site Astana.

Keywords: Pile, SLT, DLT, CPT, High-rise building

1. INTRODUCTION

Over the past two decades, there has been an unprecedented increase in the construction of skyscrapers over 150 meters in height. In Kazakhstan, it is customary to call a building more than 75 meters high (more than 25 floors) a high-rise building. These buildings can have different purposes: to be hotels, offices, residential buildings, or educational buildings. Most often, a high-rise building is multifunctional. In addition to the main purpose premises, it accommodates parking lots, stores, offices, cinemas, etc. For residential buildings whose height is unknown but whose number of floors is known, the total height is calculated according to the formula recommended by the experts of the Council on Tall Buildings and Urban Environment. For residential buildings and hotels, the floor height is taken as 3.1 m, for office buildings, 3.9 m, and for mixed-use buildings, 3.5 m. Accordingly, the inclusion criteria for buildings with an unknown height are as follows: 33 stories for residential buildings, 28 stories for mixed-use buildings, and 26 stories for office buildings. High-rise buildings (buildings with more than 75 m in height) pose new challenges to engineers, especially in the field of calculations and design of above-ground structures and foundations. Therefore, designers of both the above-ground and underground parts of the building are forced to resort to more complex calculations and design methods. This is especially true for geotechnicians who are involved in the design of foundations for high-rise buildings. In terms of complexity—complexity of design, construction, and operation—and impact on the environment and people, high-rise buildings can be classified as structures of increased danger and complexity. Buildings over 75 m require a completely different approach to design. A small number of companies work in this specific industry: just over a dozen in the USA and about ten in Europe and Asia (mainly in Japan, Malaysia and Korea).

An increase in the size of the deformable area of the base soil leads to a greater impact on the surrounding buildings and structures, including water-bearing communications, which must be taken into account in the calculation. This article discusses the experience of designing the foundations of high-rise buildings, taking into account the specified features of the types of foundations. The issues of testing heavily loaded piles and geotechnical monitoring, which are important elements in the design of high-rise buildings, are discussed in detail in previous publications [1-3]. Features of high-rise buildings impose increased requirements on the results of EGE (engineering and geotechnical elements) and must solve the following main tasks during their implementation: study of the geological structure of a mass of soils of large volumes (up to 60m in depth and at least 2 more widths of the foundation outside its contour); a reliable assessment of the hydrogeological and hydrochemical conditions, both in the compressible soil massif and in the pit zone and adjacent territory, with the establishment of their corrosive aggressiveness, in time; determination of deformation and strength properties of dispersed and rocky soils at large ranges of stress changes; instrumental observation and monitoring of deformations of the soil massif of the foundation base and the adjacent territory under static impacts [4-6]. The choice of foundation design, in addition to the principles listed above, depends on the physical and mechanical characteristics and the nature of the bedding of the foundation soils and the loads transferred to them, the shape and size of the high-rise building, the size of the construction site, the presence of surrounding buildings, tunnels (metro) and underground utilities. The basic classification of foundations of high-rise buildings is presented in Fig. 1.

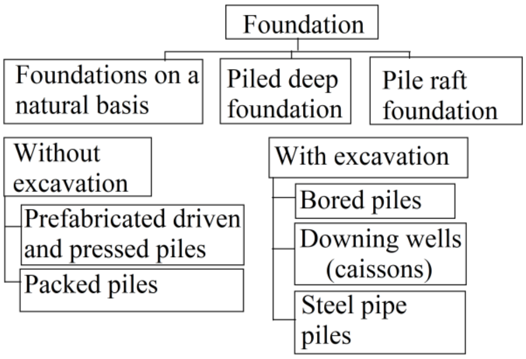


Fig. 1 Classification of foundations of high-rise buildings

The test works on piles in field conditions was carried out at the construction site, "Diamond multi-functional complex in Astana city". The Diamond Center is a mixed-use complex consisting of a 111-meter (26-story) residential tower and a 58-meter (14-story) office tower standing on a plate formed by the 2-level shopping center and associated underground car park (see Fig. 2).

The nature of the high-rise building puts it under the "Building Responsibility Level I" (Advanced) design category. The high-rise building was designed for a snow load of 100 kg/m^2, which is consistent with the requirements for Snow Region III, according to SNIP 2.01.07.-85* [7]. The extreme design temperature is -35°C. The design wind pressure was 38 kg/m^2, which is consistent with the requirements for Wind Region III according to SNIP 2.01.07.-85* [7].

Fig. 2 “Diamond” multi-functional complex

2. RESEARCH SIGNIFICANCE

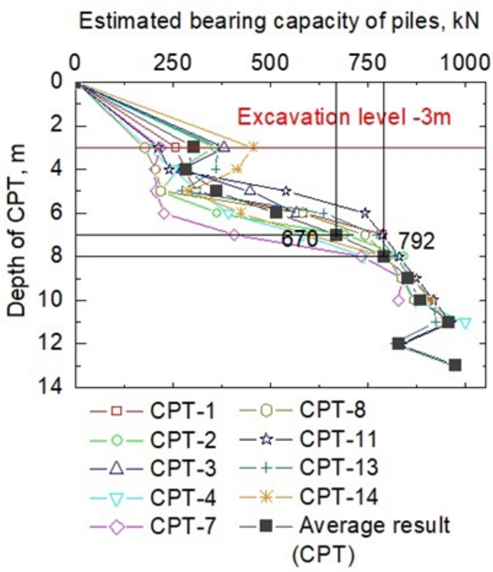
In this study, it was found that the determination by the dynamic method (according to GOST) of tests does not give an accurate bearing capacity but differs by 30-40 percent from the static one (according to GOST) [4]. An increase in the size of the deformable area of the base soil leads to a greater impact on the surrounding buildings and structures, including water-bearing communications, which must be taken into account in the calculation. The experience and results gained will be used in carrying out similar tests at this new site, as well as in the calculation and design of the tower foundations.

3. GEOLOGICAL CONDITION OF THE CONSTRUCTION SITE

Investigation of the soil layer of the construction site by the method of cone penetration test, CPT. It is carried out by immersing the probe into the ground under the action of CPT shocks at a constant speed of movement of the pressure load and measuring the soil resistance indicators. The method of CPT is a method used to determine the engineering-geological properties of the soil. Sinking of probes is carried out by sounding rigs (in most cases, drilling rigs equipped with special suspension equipment), which, in addition to the probe itself, include a device for sinking it, support-anchor devices, and measuring devices.

Probing units can be self-propelled, that is, mounted on a car or tractor; mobile trailers, that is, mounted on trailers; collapsible; or transported as an additional device attached to drilling rigs. CPT is usually carried out by continuously pressing the probe into the soil at a speed of 1.2 m/min (0.5 m/min in perennially frozen soil). Continuous (standard) and intermittent sensing are available. During continuous sounding, probe immersion breaks are allowed only to extend the probe rods. Sometimes, intermittent sounding is used, and in addition to it, in stages, at given intervals (0.5–1 m), stopping the probe is used, while soil testing is carried out according to special methods (relaxation-penetration, dissipation, and other tests). In our case, 16 tests of static sounding from the surface were carried out by drilling "leader" wells at the multifunctional "Diamond" construction site at two high elevations; the depth of investigation varies from 6.6m to 13.2 m. According to the results of CPT, the specific resistance values for the cone of the probe and the side surface of the probe were taken, and the results of soil testing by static sounding and the table for determining the bearing capacity of piles with a cross-section of 30 x 30 cm were made. Fig. 3 shows the already processed CPT results. Processing was according to the Kazakh Standard (Static sounding was performed by test-2KM-350 equipment according to GOST 20069-81 and GOST 19912-2001 to assess the bearing capacity of piles according to SNIP RK 5.01-03-2002).

Soil explorations at the high-rise building site revealed that the surface of the groundwater table was present at depths ranging from 4.9 to 5.1 m.



Note: A foundation pit was dug up to 3 meters; the calculation started from 4 meters for driven piles (4 meters for driving pile depth 1 meter), and safety factor (FS = 1.25).

Fig. 3 Calculated bearing capacity of the soils according to the results of the CPTs

The problematic nature of the soils at the high-rise building site necessitated the use of a deep foundation (driving and boring piles). Traditionally, deep foundations have largely consisted of driven piles. The driving of such piles is, however, somewhat limited by their cross-sectional dimensions and by the strength of the material from which the pile is made. The construction of ever taller structures imposes increasing loads on the foundation, thus necessitating an increase in the diameter, length, and strength of the piles. In the case of the high-rise building, a deep foundation consisting of 1200 mm diameters and 26.5 and 28.14 m long bored piles was found to be the most optimal solution (see Fig.4).

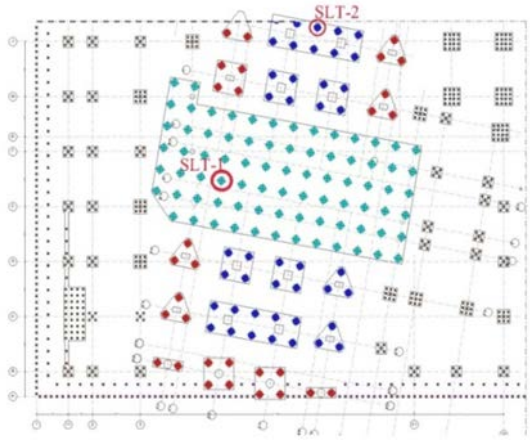


Fig. 4 Location of bored pile foundations Multifunctional complex "Diamond"

In Fig. 4, bored pile foundations are shown in different colors. Bored piles of green color, 26.5 meters long and 1200 mm in diameter, with a design pile load of 6268 kN. Bored piles of red color with a length of 25 meters and a diameter of 1200 mm and a design load per pile of 8336 kN, as well as bored piles of blue color with a length of 28 meters and a diameter of also 1200 mm and a design load per pile amounted to 10598 kN.

4. DYNAMIC AND STATIC PILE LOAD TESTS FOR DRIVEN PILES

4.1 Dynamic Load Test by GOST

Pile driving was carried out on July 21, 2021, with "Junttan PM-20 LC" hydraulic hammer NNK-5A (5000 kg) equipment. To prevent pile heads from breaking, special wooden mats were used. During the test, the number of hammer blows and the fall height of the hammer impact part were calculated at each meter of the pile sinking into the soil layer, and the fall height and number of the hammer impact part in every 10 cm were recorded in the last meter. During the pile driving, the residual stop (refusal) of the pile was from 0.42 cm to 1.11 cm in the last 10 cm of the pile, when the impact energy of the hammer was from 2.5 tm to 3.5 tm. Repeated pile driving was carried out on July 28, 2021, with the same equipment, 7 hours after the end of pile driving, with two systematic procedures consisting of three and five blows. During the repeated driving of the piles, a 10 cm measuring ruler with a distance of

1mm was attached to the pile. Control of piles sinking into the soil layer was carried out with the help of a leveler. During repeated pile driving, the residual pile stop (refusal) ranged from 0.30 cm to 0.64 cm in the last 10 cm of the pile when the impact energy of the hammer was 2.5 tm. To determine the load-bearing capacity of the piles, the largest of the average values of the residual failure (refusal) of the pile, consisting of three and five blows, was obtained during re-driving after the "rest" of the piles [3-6]. The driven piles were of different lengths from 3 to 4.1 meters, depending on the bearing capacity, according to the results of dynamic as well as static studies. The results of the test by static and dynamic methods provided the design load.

4.2 Processing of Dynamic Test Results of Piles

The normative values $F_{u,n}$ of the ultimate resistance of the piles are equal to the average values of the values of the individual ultimate resistances obtained during the tests.

Where n is the number of tests or the number of piles to be tested, F_i is equal to the individual limit resistances obtained according to the results of dynamic tests. Performs a statistical check to avoid possible errors. If the conditional value for F_i is fulfilled, Eq. (1):

$$F_{u,n} = \frac{1}{n}\sum_{i=1}^{n} F_i, \quad (1)$$

$$[F_{u,n} - F_i] \triangleright vS \quad (2)$$

Where, v is the accepted statistical criterion due to the number of tests n=11, v=2.47 (GOST 20522-96 "Methods of statistical processing of test results"); S is calculated according to the following Eq. (3):

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(F_{u,n} - F_i)^2}, \quad (3)$$

If any value is omitted, $F_{u,n}$ and S must be recalculated for the remaining test data.

We find the value of S and check; in our case, everything is correct, and the value of F_i is sent to the next static processing. In the following, the reliability coefficient γ_g, the coefficient of variation V, and the accuracy index of its average value ρ_a are determined for the soil:

$$V = \frac{S}{F_{u,n}}, \quad (4)$$

$$\rho_a = \frac{t_n V}{\sqrt{n}}, \quad (5)$$

$$\gamma_g = \frac{1}{1 \pm \rho_a}, \quad (6)$$

Where, t_α is the coefficient at reliability probability α and number of degrees of freedom $n-1$ (GOST 20522-96 "Methods of statistical processing of test results") [7]. Bearing capacity of piles taking into account the reliability factor, γ_g (see Table 1).

Table 1 Result of the Dynamic Load Tests

#	Pile	Depth, m	Bearing capacity, kN	FS -1.4, kN
1	TP-7	4.1	674	481
2	TP-12	3.1	620	443
3	TP-16	3.1	620	443
4	TP-18	3.5	620	443
5	TP-22	3.0	620	443
6	TP-34	3.6	615	439

4.3 Methodologies of the Pile Field Test (SLT) by GOST

Field tests of soils with piles on the territory of Kazakhstan and in the CIS countries are carried out in accordance with the requirements of GOST 5686-12 [4].

The piles were unloaded in stages equal to the double values of the loading stages, with the observation of elastic deformations at each stage for 15 minutes. After complete unloading (to zero), observations of elastic movements were carried out for 1 hour, with reports taken every 15 minutes.

Soil testing by static loads on piles is carried out in the following order [8-13]: the rest of the pile is maintained after the installation of the bored pile; testing of soils with bored piles begins not earlier than the pile concrete reaches 80% of the design strength; the pile is loaded with a static vertically indenting, stepwise increasing load, in steps; loading is performed by Three 500-ton hydraulic jacks model DG500G250; instrument reports are taken in the following sequence: the first report is taken immediately after the load is applied, then four readings every 15 minutes, two readings with an interval of 30 minutes and then after 60 minutes until conditional stabilization, that is, when the difference in displacements ΔS is not more than 0.1 mm for the last 1.00 hour of observation: the vertical load is brought to a value that causes the pile to move by at least 40mm or to the maximum load provided for by this program; unloading of the tested piles is carried out in steps equal to double the loading steps; readouts on strain gauges are taken immediately after each stage of unloading and observed after 15 minutes.

After complete unloading (to zero), the elastic displacements are monitored for 1 hour with readings taken every 15 minutes.

4.4 Static Load Tests (SLT) of Driven Piles

Static Load Test (further SLT) is one of the most reliable field tests for analyzing pile bearing capacity. SLT should be carried out for driven piles after the "rest." SLTs were carried out for six piles on the construction site (see Fig. 5). The measured relationships between the pile head load, *L*, and the head displacement, *S*, of the test piles are shown in Fig 6. As a calculation chart to define the design load and bearing capacity of driven piles. A graph of the relationship between piling settlement *S* from load P and the changing of pile displacement *S* on time *t* was constructed on the result of the static load test. The results are presented in Fig. 6. Bearing capacity F_d on the result of the field static load test is determined by Eq. (7):

$$F_d = \gamma_c \frac{F_{u.n}}{\gamma_g}, \quad (7)$$

Where, γ_c is the coefficient of working condition received during the load activity, which is the usual $\gamma_c = 1$; $F_{u.n}$ is the guideline value of pile limited resistance; and γ_g is the safety factor on the ground, which equals 1.2 [14-19].

Fig. 5 Driven pile test for static compression

According to the SLT result, the load-settlement diagrams were drawn (see Fig. 6).

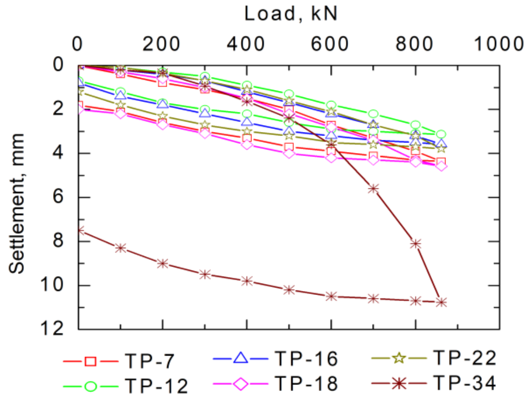


Fig. 6 Results of Static load tests of driven piles

As a result of the static load test, the bearing capacity of driven piles is 861 kN. Allowable bearing capacity of the piles with an allowance for safety factor (FS = 1.2) equal to piles = 717.5 kN (see Table 2).

Table 2 Result of the static load tests

#	Pile	Dept h, m	$F_{u.n}$, kN	S, mm	F_d,kN
1	TP-7	4.1	861	4.37	717.5
2	TP-12	3.1	861	3.13	717.5
3	TP-16	3.1	861	3.59	717.5
4	TP-18	3.5	861	4.58	717.5
5	TP-22	3.0	861	3.79	717.5
6	TP-34	3.6	861	10.77	717.5

5. STATIC PILE LOAD TESTS FOR BORING PILES

Static Load Test Method (hereinafter «SLT») Static loading is designed to determine the carrying capacity of piles in the soil on the side surface and underside and to establish the dependence of the piles movement in the soil of the load by testing them in conditions of the construction site, carried out in a set of design and survey work and control tests during construction. The SLT piles are tested with axial indentation forces applied to the pile heads in the form of stepped, increasing static loads. The tests are performed without affecting the serviceability, strength, or and load-bearing capacity of the piles and are in accordance with the requirements of GOST 5686-12. One of the main advantages of the method is the ability to use the tested pile in a structure. For static tests, a special stand is used where the load is created by hydraulic jacks. One of the most reliable ways to quantify the load-settlement response of piles and to determine their bearing capacity at a specific site is through field static load tests (SLTs). According to the requirements of the Kazakhstan Standard SNIP RK 5.01-03-2002 and SNIP RK 5.01-01-2002, depending on the category of construction, the ultimate value of settlement of the tested pile is between 8.91 mm and 10.61 mm (pile test load 13000 kN). At the high-rise building site, the SLTs were performed 21 days after the 1200 mm diameter and 26.5 m and 28.14 m long bored pile had been installed (Fig. 7).

Fig.7 Static load tests boring piles in construction site high-rise building "Diamond"

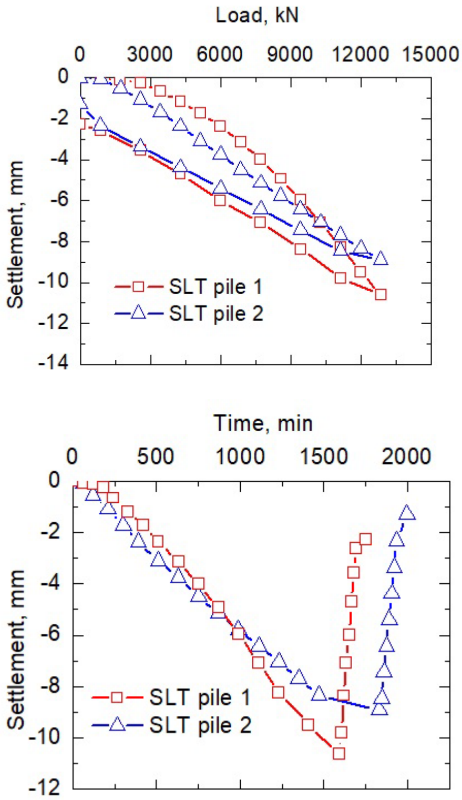


Fig. 8 Load-settlement and time-settlement curves for the SLTs in the construction site high-rise building "Diamond"

The SLTs were carried out in accordance with the requirements of GOST 5686-2012. Fig. 7 shows the layout of the piles and the locations of the SLTs at the high-rise building site. The latter are denoted by "Pile 1", and "Pile 2" in the aforementioned figure. Fig. 7 shows the set-up of the SLT and the platform pile layout. The foundation of the structure is laid out in the form of a grillage in which there is a technical room for the storage and maintenance of equipment.

Two of the bored piles were subjected to static, stepwise compressive indentation loading with load increments equal to 857.14 kN. The maximum load on each of these two piles was 13000 kN. The settlement maximums measured in these two tests were 10.61 mm and 8.91 mm. Fig. 8 and Table 3 present the load-settlement and time-settlement curves for the SLTs performed at the high-rise building site [20-25].

It should be noted that even at the maximum test load of 13000 kN, only the elastic work of the pile in the ground is evident, as evidenced by the slight residual settlement of the soil after unloading of 1.3 mm and 2.92 mm (see Table 4).

The allowable bearing capacity of the piles with an allowance for safety factor (FS = 1.2) is equal to 10833 kN (see Table 4) [8].

Table 3 Results of the static and dynamic load tests

#	Pile	S, mm	F_d (SF), kN	%
Static load tests driven piles, FS = 1.2 (SLT by GOST)				
1	TP-7	4.37	717.5	100
2	TP-12	3.13	717.5	100
3	TP-16	3.59	717.5	100
4	TP-18	4.58	717.5	100
5	TP-22	3.79	717.5	100
6	TP-34	10.77	717.5	100
Dynamic load tests driven piles, FS = 1.4 (DLT by GOST)				
1	TP-7		481	67
2	TP-12		443	62
3	TP-16		443	62
4	TP-18		443	62
5	TP-22		443	62
6	TP-34		439	61

Cone penetration tests, FS = 1.25 (CPT by GOST)					
	CPT	7m, FS	8m, FS	For 7m %	For 8m %
1	Average result*	536	633	75	88

**Note: (CPT) A foundation pit was dug up to 3 meters, the calculation starts from 4 meters for driven piles (4 meter for driving pile depth 1 meter), and safety factor (FS = 1.25)*

Table 4 Results of the static load test (boring pile)

Pile	Depth, m	S, mm	F_d, kN
Pile-1	26.5	10.61	10833
Pile- 2	28.14	8.91	10833

6. CONCLUSION

The existing pile foundation standards practiced in Kazakhstan are outdated and urgently need to be modernized. This article provides very brief descriptions of the upcoming changes in the concept of pile foundation design.

When testing piles for bearing capacity by static and dynamic methods (according to GOST), it was found that the dynamic test method is 30-40 percent lower, and the calculated CPT method (according to GOST) is 15-20 percent lower. Therefore, the dynamic method (according to GOST) needs to be modernized.

The results of two vertical static load tests showed that the maximum proof load carried by these piles was 13000 kN. The associated maximum settlements were 10.61 mm and 8.91 mm, using a factor of safety of 1.2, the allowable bearing capacity of the piles is thus 10833 kN. It should be noted that even at the maximum test load, only the elastic work of the pile in the ground is evident, as evidenced by the slight residual ground settlement after unloading, which is 1.3 mm and 2.92 mm, respectively.

The results of the static load tests are important for understanding the soil-structure interaction for the high-rise building.

7. ACKNOWLEDGMENTS AND FUNDING

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