DOI 10.1007/s11204-019-09579-6
Soil Mechanics and Foundation Engineering, Vol. 56, No. 2, May, 2019 (Russian Original No. 2, March-April, 2019)

EXPERIMENTAL INVESTIGATIONS

ESTIMATING THE DRIVEN PILE CAPACITIES FOR COF PROJECT IN WEST KAZAKHSTAN

A. Zhussupbekov,[1] Der-Wen Chang,[2] Y. Utepov,[1] K. Borgekova,[1*] and A. Omarov[1]
[1]L.N. Gumilyov Eurasian National University, Astana, Kazakhstan;
[2]Department of Civil Engineering, Tamkang University, Taipei, Taiwan,
[*]Corresponding author E-mail: borgekova@bk.ru.

UDC 624.131.524.4

This paper presents estimations of bearing capacities of precast concrete joint piles at two construction sites in the regions of Port Prorva located in Western Kazakhstan. The capacities of the piles were predicted using the static pile load test data with the conventional interpretation methods. The results were compared to those from APILE analyses, analytical calculations based on the Kazakhstani standard method, and the pile driving analyzer. It was shown that the highest pile capacities were obtained from the Chin interpretation and Decourt extrapolation methods. The results from De Beer, Davisson, and Fuller and Hoy interpretation methods were found to be similar. The result from the Butler and Hoy interpretation method was similar to the ones obtained from pile driving analyzer and APILE analyses. The pile capacity obtained by the Kazakhstani standard method was found slightly higher, though it is applicable for estimating ultimate pile capacities. The yield capacity of the piles was determined under working loads. The methods used in the paper can also serve as practical guidelines to assess the capacities of driven piles installed in the field.

Introduction

In 2017, a new Cargo Transportation Route was constructed from the Northeast Caspian Sea to Tengiz for creating an access channel to the new facility at the port of Prorva, which was designed as a berth for offloading heavy vessels and barges. The berth was given the project name of Cargo Offloading Facility (COF) [1].

The COF is located along the quay and represents a special reinforced concrete surface supporting large cranes needed to unload both bulky and general cargo. Sheet pile walls were built surrounding the COF surface. According to the design drawings, the COF construction site was planned by installing precast concrete joint piles (PCJP). This is the first example of installing such piles in Kazakhstan. Applying PCJPs for the first time demanded a comprehensive engineering approach. Therefore, it was decided to first conduct pile load tests at a pilot site. In this study, the pilot site and the COF site are referred to as construction sites A and B, respectively.

The boreholes were drilled before installation of piles. The drilling allows piles to sink in the vertical direction to a certain depth so as to reduce the noise incurred during the pile driving. The boreholes were made with pre-augering and pre-drilling methods. The pre-augering was executed by a clockwise rotating auger insertion up to the designated depth; the auger was then removed in a counterclockwise direction. With this method, an amount of soil was removed from borehole. In the pre-drilling method, such removal was performed without rotation.

Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 2, p. 26, March-April, 2019.
0038-0741/19/5602-0121

PCJPs consisted of two segments, each having a cross-section of 400 × 400 mm. The length of bottom segment was 16.0 m, whereas the upper segment was either 9.5 or 11.5 m in length. The head of the bottom segment and the bottom of upper segment were connected by locking steel plates. The locking mechanism, in turn, protects the joint. Piles were coated with corrosion protection material (bituminous) and marked with cross-lines every 0.25 m. Before driving the bottom segment, to the pile top was attached a 6 cm thick nylon plate (Emeca) which had a yield stress of 72 MPa. The hammer helmet was attached by wooden plate. Both plates were used to preserve the pile head in good condition during driving.

Methods of testing and analysis

The study started with dynamic tests using the PDA method. The PDA is a semi-empirical tool to interpret pile capacity [2, 3]. Although this method was developed based on stress wave theory to analyze the vertical load behavior during pile driving, there are a couple of physical quantities that are difficult to identify and calibrate in practice. The difference between the kinematics exerted during pile driving into soils and the static loading resistance of the pile-soil system needs to be carefully assessed.

Following the PDA tests, piles were tested by applying static loads. A static load test (SLT) allows for the determination of the degree of pile settlement, depending on the load applied over time, and facilitates the creation of load-settlement curves [4, 5]. There are many interpretation methods that can be used to analyze the pile load test data. In this study, a number of such methods, discussed in greater detail by Fellenius [6, 7], were adopted to assess the pile capacities.

The aforementioned interpretation methods are empirical in nature. In order to verify their results, pile capacities obtained from the APILE analysis [8] were also made. The APILE analysis is based on the finite difference analysis of a single pile under vertical loading. The so-called t–z and Q–z curves representing the load transfer and the displacement of the soil along the shaft and at the pile tip were used to model the nonlinear soil behavior in response to pile loading. Such analyses, which can provide an approximate computer-based stress-deformation analysis, have been increasingly adopted in routine design of piles. Of course, the reliability and applicability of such solutions depend on the modeling assumptions and on the model parameter values used in the analysis.

The pile capacities can be also verified using simple calculations involving analytical equations for pile capacity. There are many different versions of such equations for pile capacity computations; all of these involve some estimation of the friction and the end bearing resistance. The analytical approach used in this study followed the Kazakhstani standard "Pile foundations" [9].

The ultimate pile capacities are very difficult to obtain in the field since relatively large displacements are required to fully mobilize all the friction and end bearing. Typically, the attainment of such displacements is not feasible in the field. As such, most of the pile load tests do not yield the same results as hand calculations; instead, the field results tend to be less than those obtained from hand calculations.

Soil profile information

The ground water level in the Caspian Sea depends on a balance between the inflow of river water and evaporation. Major Caspian Sea level fluctuations are closely related to Pleistocene glacial and interglacial periods. The project area was situated on the Northern Caspian Shelf. At present, the North Caspian Sea has a limited water depth (maximum 5 to 8 m). The physical and mechanical characteristics obtained from laboratory tests on soil samples at construction sites A and B are shown in Table 1.

Field tests

Seven PCJPs were tested in the field: three at construction site A, and four at construction site B. All the piles were first tested by the PDA method (while driving) and, five days after driving, by a SLT. In this study, piles were given identification codes A_1-A_3 and B_1-B_4.

TABLE 1

Layer thickness, m	Soil type	General consistency	γ_{sat}, kN/m^3	φ, deg	S_u, kPa
Construction site A					
0.5	Silt, slightly organic, calcareous	soft to firm	9.3	29.4	-
4	Sand, silty, calcareous	medium dense to dense	20.2	31.5	-
4	Clay, silty, calcareous	stiff	19.1	24.7	80
19	Clay, silty, calcareous	very stiff	20.2	24.7	150
Construction site B					
4	Sand, silty, calcareous	medium dense to dense	20.2	31.5	-
4	Clay, silty, calcareous	stiff	19.1	24.7	80
4	Sand, silty, calcareous	very dense	20.0	31.8	-
5	Clay, silty, calcareous	very stiff	20.6	23.8	150
10	Clay, silty, calcareous	very stiff	20.2	24.7	150

TABLE 2

Pile ID	A_1	A_2	A_3	B_1	B_2	B_3	B_4
Length, m	25.5	27.5	25.5	27.5	27.5	27.5	27.5
Penetration length, m	24.25	26.25	22.5	25.63	25.4	25.86	25.78
Type of boreholes	Pre-augering; ∅330 mm; L = 12.0 m	Pre-augering; ∅330 mm; L=12.0 m	Pre-augering; ∅330 mm; L = 9.0 m	Pre-drilling; ∅330 mm, L = 12.0 m	Pre-drilling; ∅330 mm , L = 12.0 m	Pre-drilling; ∅330 mm, L = 12.0 m	Pre-drilling; ∅440 mm , L = 15.6 m
Max. settlement, mm	20.0	34.04	31.53	16.22	7.38	4.43	6.89

The dynamic tests of PCJPs were carried out by the PDA method using model PAX with piling machine JUNTTAN PM25LC that used a hydraulic hammer HHK-9A with a weight of 9 tons and a 990 kg head-cap. Attached to the tested PCJPs was a set of accelerometers and strain transducers at a distance of two widths (i.e., 80 cm) below the pile head. The sensors were connected to the PDA hardware via special cables. PDA internally performs all the necessary signal conditioning and processing to obtain output results during driving. For each hammer blow, it immediately displays on the monitor screen the measured force at the pile head (F_{m}) and pile head velocity (v_{m}) as a function of time. After completion of the dynamic tests, the acquired data was analyzed by the Case Method & iCAP® using the software PDIPLOT2. Average bearing capacities of tested PCJPs are: for A_1 – 2202, A_2 – 1768, A_3 – 2497, B_1 – 2518, B_2 – 2203, B_3 – 2502, B_4 – 1722.

SLTs of PCJPs were carried out according to the requirements of ASTM D1143 (Standard Test Methods for Deep Foundations Under Static Axial Compressive Load) [10]. Three SLTs (400 × 400 mm) were conducted with a maximum load of 3278 kN at construction site A and four tests were conducted with a maximum load of 1639 kN at construction site B (Table 2).

Pile bearing capacities from interpretation methods

An estimation of the bearing capacity of tested PCJPs was performed by the following methods: Davisson, Chin, De Beer, Fuller and Hoy, Butler and Hoy, and Decourt Extrapolation [6, 7].

Figure 1a shows the load-settlement curves obtained using the Davisson method. In this method, the bearing capacity is determined using an offset or "Davisson limit," consisting of a line parallel to the initial tangent to the load-settlement curve. This method was suggested in conjunction with the wave equation analysis of driven piles and has gained widespread use with time [6]. The Davisson limit (offset) is defined as a limiting load corresponding to the movement exceeding the elastic compression of a pile by an offset of 3.8 mm, plus a factor equal to the pile diameter (in mm) divided by 120. In the case of a 400 mm square PCJP, the radius of a circle circumscribing the square is mm. Dividing this equivalent diameter by 120 and adding this quotient to 3.8 mm gives an offset of 8.52 mm. The offset is applied as shown in Fig. 1a, giving a pile capacity of 2873 kN.

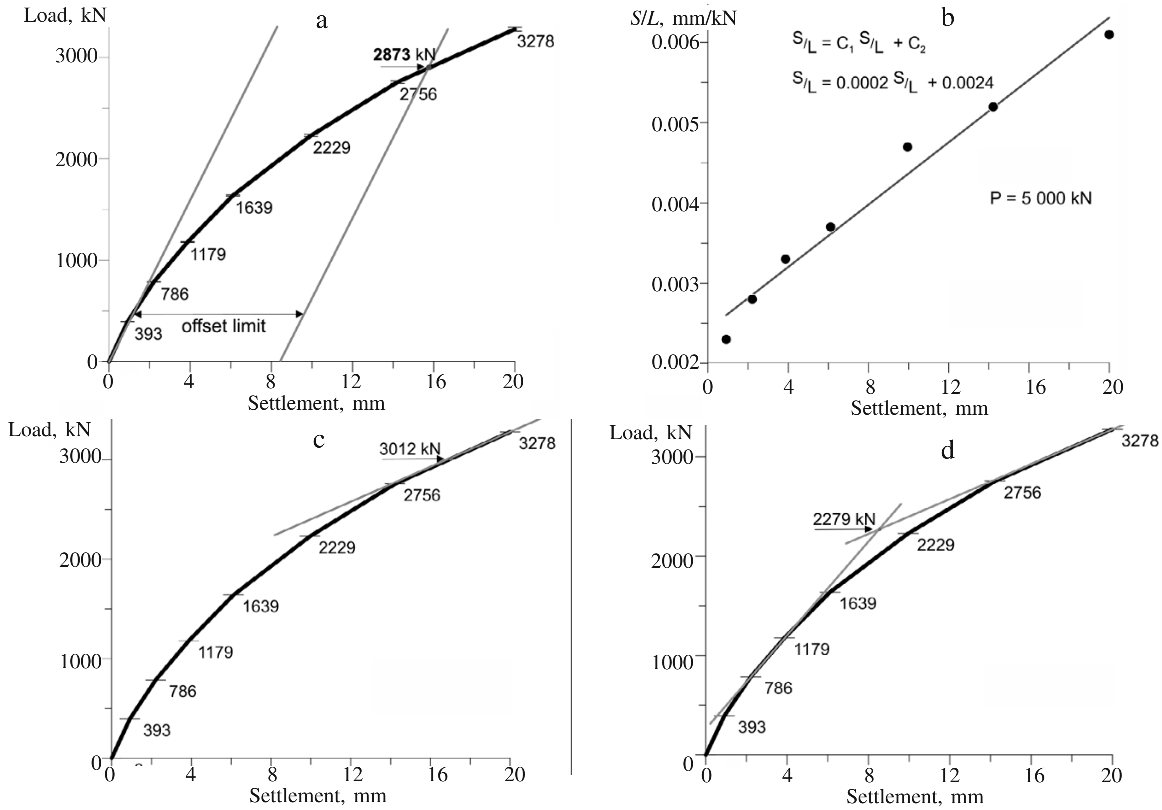

Fig. 1. Pile A_1 capacities interpreted by: a) the Davisson, b) the Chin, c) Fuller and Hoy, and d) Butler and Hoy methods.

In the Chin method [6], each settlement value is divided with its corresponding load value. The resulting value is plotted against the settlement and a trend line is drawn on the plot as shown in Fig. 1b. The inverse slope of this line is the Chin pile capacity P [6]:

$$P = 1/C_1, \tag{1}$$

where C_1 is the slope of the straight line shown in Fig. 1b.

In the approach proposed by Fuller and Hoy [6], the pile capacity is equal to the test load at which the inverse slope of the load-settlement curve is equal to 0.14 mm/kN (Fig. 1c).

In an extension to the Fuller and Hoy approach, Butler and Hoy [6] defined the pile capacity as the load at the intersection of the aforementioned inverse slope and the tangent to the initial straight line portion of the load-settlement curve. Since it is more or less parallel to the elastic line, a line that is parallel to the rebound portion of the curve can also be used, and often is preferred to the initial straight line portion (see Fig. 1d).

Figure 2a presents a method proposed by De Beer [6], where the load-settlement values are plotted on a double logarithmic diagram. When the values fall on two approximately straight lines, the intersection of these defines the bearing capacity.

The results of Decourt method [7] are shown in Fig. 3b. The construction used in this method is similar to that used in Chin's method [6]. To apply the method, one needs to divide each load by its corresponding settlement and plot the resulting value against the applied load. The Decourt extrapolation load limit [7] is then equal to the ratio between the y-intercept and the slope of the line:

$$P = C_2/C_1, \tag{2}$$

where C_2 is the y-intercept of the straight line.

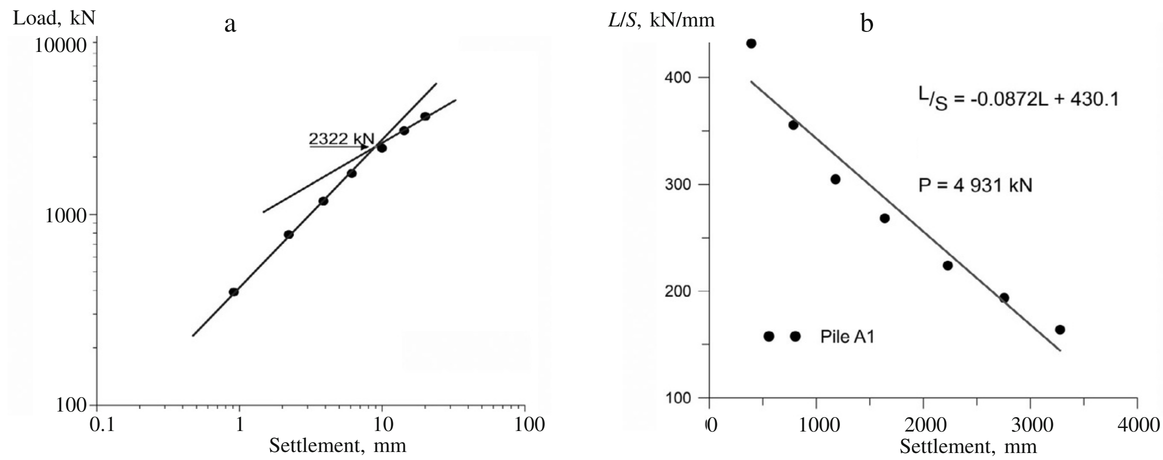

Fig. 2. Pile A_1 capacities interpreted by: a) De Beer and (b) Decourt methods.

TABLE 3

Methods	Ultimate pile capacity, kN						
	A_1	A_2	A_3	B_1	B_2	B_3	B_4
Davisson	2873	2400	2609	1223	–	–	–
Chin	5000	5000	5000	2000	2500	3333	2500
De Beer	2322	2287	2584	1132	1050	1077	1168
Fuller and Hoy	3012	3025	3028	1070	1325	1295	1326
Butler and Hoy	2279	2224	2445	656	913	1002	1089
Decourt Extrapolation	4931	4624	4988	1836	2555	3319	2495

Table 3 compares the results obtained using the six methods considered herein. From a comparison of these results, it is evident that the Chin and Decourt methods give similar results and show the highest values for pile capacity. The Butler and Hoy method [6] gives the lowest pile capacity. The Davisson, De Beer, and Fuller and Hoy methods [7] fall in between these two extremes.

Pile Capacities from APILE Analysis

The physical and mechanical characteristics (Table 1) were used in performing APILE analyses. These analyses were conducted during a short-term exchange program of study at the Department of Civil Engineering of Tamkang University, Taiwan. The capacity of a single pile under axial loading was determined using four methods: 1) the American Petroleum Institute (API), 2) the U.S. Federal Highway Administration (FHWA), 3) the U.S. Army Corps of Engineers (USACE), and 4) the Lambda method. Table 4 summarizes the ultimate pile capacities for each of the seven PCJPs, obtained using these four methods; also shown is the average value for each pile. It is interesting to note that the pile capacities obtained using these four methods do not differ very much, regardless of the construction site. Finally, it is timely to note that, due to the limitations of APILE Plus software, the silty layer of site A with a thickness of 0.5 m was not taken into account in the calculations.

Pile Capacities from Kazakhstani standard

Depending on whether the pile bottom rests on a certain soil layer or on rocky soil, driven piles are referred to as being "hanging" or "standing," respectively. The PCJPs considered within the current study qualify as hanging piles. For such piles, the Construction norms and rules of the Republic of Kazakhstan (SNiP RK) Pile foundation [9] regulates hand calculations of bearing

TABLE 4

Methods	Ultimate pile capacity, kN						
	A_1	A_2	A_3	B_1	B_2	B_3	B_4
API	2430	2744	2130	2269	2164	2269	2269
FHWA	2314	2521	2108	2517	2466	2517	2517
USACE	2332	2572	2092	2062	2006	2062	2062
Lambda	2088	2337	1848	2019	1956	2019	2019
Average	2291	2544	2045	2217	2148	2217	2217

TABLE 5

Methods	Pile capacity, kN						
	A_1	A_2	A_3	B_1	B_2	B_3	B_4
Chin, Decourt, average	4966	4812	4994	1918	2528	3326	2498
De Beer	3000	3250	2714	1750	1750	1000	963
Davidson	2870	2500	2717	1223	–	–	–
Fuller and Hoy	2500	2900	2900	1000	1000	1300	1391
Butler and Hoy	2100	2208	2520	643	967	980	900
PDA	2202	1768	2497	2518	2203	2502	1722
APILE, average	2291	2544	2045	2217	2148	2217	2217
[9]	2836	3043	2670	2828	2794	2846	2840

capacity representing an aggregate of end bearing capacity and pile lateral surface friction against soil layers. This statement is formulated as follows:

$$F_d = \gamma_c(\gamma_{cR} RA + u\sum \gamma_{cf} f_i h_i), \tag{3}$$

where F_d is the pile bearing capacity; γ_c is the coefficient for the pile operating conditions in the soil (γ_c = 1.0 for the PCJPs); γ_{cR} = 1.0 and γ_{cf} = 1.0 are the coefficients of soil operating conditions on the pile toe and by pile surface. respectively, according to [9]; R = 8700~9100 kPa is the design resistance of soil on a pile toe [9]; A = 0.16 m^2 is the area of pile cross section, u = 1.6 m is the outer perimeter of pile cross-section, f is the design resistance of the i-soil layer on pile skin according to [9] (for sites A and B: f_1 = 15, f_2 = 35, and f_3 = 44, and f_4 for site A is equal to 72~76 kPa and for site B f_4 = 46, f_5 =51, f_6 = 82 kPa), and h_i is the thickness of the ith soil layer in contact with the pile skin (see Table 1). The results of hand calculations of PCJP bearing capacity obtained using Eq. (3) [9] are: 2836 for pile A_1; 3043 for A_2; 2670 for A_3; 2828 for B_1; 2794 for B_2; 2846 for B_3; and 2840 for B_4.

Discussion

Estimates of bearing capacity of the PCJPs tested at construction site A (where the maximum applied load was 3278 kN) by a variety of interpretation methods showed that the Chin and Decourt methods [6, 7] gave the highest values. The remaining interpretation methods provided results more or less similar (2000~3000 kN) to those obtained from the APILE analyses, PDA, and hand calculations. Meanwhile, the bearing capacities of PCJPs at construction site B (where the maximum working load was 1639 kN) obtained using the De Beer, Fuller and Hoy, and Butler and Hoy methods [6], were considerably lower than those obtained from the APILE analyses, PDA, and hand calculations (Table 5). This seems to be obvious, since the APILE, PDA, and hand calculations are only appropriate for prediction of ultimate bearing capacity. For the working load tested piles at construction site B, the interpretation methods only predicted yield capacities that were about 1/2 to 1/3 of the ultimate capacities. In general, despite the different approaches used, the results were found to be rational, and consistent with Kazakhstan construction requirements [9].

The bearing capacities of PCJPs under the ultimate and working loads in the COF Project in West Kazakhstan were examined with pile load test data using different interpretation methods. These results were compared to those obtained from PDA, APILE analyses, and hand calculations according to Kazakhstan standards.

For the ultimate load, it is found that the Chin and Decourt methods give the highest values for both construction sites A and B. The De Beer, Davisson, and Fuller and Hoy methods were found to be more or less similar for the site A values. Results from the Butler and Hoy method for site A were almost similar to the ones from the PDA method and the APILE analyses. Hand calculations presented the second highest results at both sites (second only to the Chin and Decourt methods), and clearly represent rational approaches.

For the yield load, all interpretation methods except the Chin and Decourt gave lower predictions. This is reasonable, because the results from the PDA method, APILE analyses and hand calculations are only really appropriate for the prediction of ultimate bearing capacity.

The ultimate capacities of PCJPs at construction site A are reported as 2000~2500 kN, while the yield capacities of the PCJPs under working load at construction site B are reported as 1000~1500 kN. The ultimate capacities of these piles at construction site B are reported as 2000~3000 kN. The factor of safety for the allowable capacity can thus be satisfied according to the local design specifications.

The bearing capacity of the PCJPs was determined from APILE by using engineering-geological data of the project. According to the analysis, it was observed that the results obtained from the APILE analyses were similar to those from the PDA method and from the hand calculations. The differences in ultimate bearing capacity of piles subjected to 3278 kN were insignificant.

Although the present results were for PCJPs, they can likewise be referred to the determinations of the bearing capacities of driven piles. The interpretation methods, hand calculation, APILE analyses, and PDA method are thus all applicable to pile designs and analyses involving the problematic soils.

Acknowledgments

The current study involving PCJPs tested at the construction site of Prorva was made possible due to the consent of KGS-Astana Ltd. The study was also supported by the Geotechnical Institute (GI) of the L.N. Gumilyov Eurasian National University (Grant No.11/KGS from 25.04.2017). The authors are grateful to KGS-Astana and GI for supporting this research activity.

REFERENCES

1. A. Zhussupbekov, I. Morev, A. Omarov, K. Borgekova, and G. Zhukenova, "Geotechnical considerations of piling testing in problematical soils of West Kazakhstan," *Int. J. GEOMATE*, **15**, No. 47, 111-117 (2018).
2. A. Zhussupbekov, A. Omarov, G. Zhukenova, and G. Tanyrbergenova, "Pile Foundations of Mega Projects: New Railway Station and LRT in Problematical Soil Ground of Astana," *Procedia Eng.*, **189**, 511-518 (2017).
3. A. Zhussupbekov, R. Lukpanov, and A. Omarov, "The Results of Dynamic (Pile Driving Analysis) and Traditional Static Piling Tests in Capital of Kazakhstan," *Proc. 13th Baltic Sea Region Geotechnical Conference*, Vilnius, Lithuania, 201-205 (2016).
4. A. Zhussupbekov and A. Omarov, "Modern Advances in the Field Geotechnical Testing Investigations of Pile Foundations," *Procedia Eng.*, **165**, 88-95 (2016).
5. A. Zh. Zhussupbekov, R. E. Lukpanov, and A. R. Omarov, "Experience in Applying Pile Static Testing Methods at the Expo 2017 Construction Site," *Soil Mech. and Found. Eng.*, **53**, 251-256 (2015).
6. B. H. Fellenius, "The analysis of results from routine pile load tests," *Ground Eng.*, **13**, 19-31 (1980).
7. B. H. Fellenius, "What capacity value to choose from the results a static loading test. We have determined the capacity, then what?", *Deep Found. Inst.*, 19-26 (2001).
8. L. C. Reese, S. T. Wang, and J. Arrellaga, *Computer Program APILE Plus for the Analysis of the Axial Capacity of Driven Piles*, Austin, Texas (2007).
9. SNiP RK 5.01-03-2002. Pile Foundation, Astana, Kazakhstan [in Russian] (2002).
10. ASTM D1143. Standard Test Methods for Deep Foundations Under Static Axial Compressive Load, ASTM International, USA (2007).