Investigations of piles by bidirectional static loading test in Astana soils

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Abstract. The article presents the results of vertical static load tests of diametral and deep bored piles specially conducted at the construction site of EXPO-2017 in Astana, Kazakhstan. The methodology for determining the bearing capacity of the pile is summarized. Bored piles with a length of 31.5 m and a diameter of 1000 mm were tested. Vertical static load tests were conducted for the following load configurations: Bidirectional Static Loading Test (according to ASTM D8169), Static Compression Loading Test according to ASTM D1143-07 and Static Loading Test according to GOST 5686-12. The method presented in the paper can serve as practical guidelines to assess the capacities of bored piles installed in the field. This geotechnical investigation is important for understanding the soil-structures interaction on difficult soil ground conditions related to the construction sites.

1 Introduction

The most reliable way of estimating the ultimate bearing capacity of the piles under vertical loads is to apply the static axial loading test. These experiments are carried out by measuring the settlements of the piles against these loads by applying predetermined loads to the pile. It is estimated that from the data obtained as a result of these experiments, the settlement of the pile will take place on the service load and ultimate load. As a result of these obtained results, it is reached that the load bearing capacity of other piles to be produced in the project area will be sufficient.

Static loading experiments are a type of pile loading experiments. Axial pressure and axial tensile tests are the types of static loading experiments. The standards used for these experiments are ASTM D 1143-81 (1994), ASTM D-3689 (1995), ASTM D 3966-90 (1995), ASTM D 3966-07 (2013), ASTM D-1143/D1143M (2013), ASTM D1143/D1143M-20 (2020), GOST 5686-2020 (2020). [1-6] The principles of the experiments and the points to be noted are detailed in these standards.

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Until the early 50s of the last century, the only method for determining the sediment of single piles was the Vertical static test method (Top down), which allows to establish the dependence of sediment on the load S = f (P). The works of A.A. Luga, H.R. Khakimov, A. A. Bartolomey are based on the processing of large the number of tests of piles of different lengths in different geological conditions. On the basis of these treatments, dependencies are obtained that make it possible to establish the precipitation of single piles without resorting to expensive static tests. The works of E.P. Sivtsova, L.B. Ogranovich, G.S. Ter-Ovanesov are based on the application of Mindlin's formula for the vertical component of displacement from the force applied inside the half-space. V.A. Golubkov established the dependence of precipitation on load based on experimental studies and analysis of the work piles. A. Kezdi proposes to determine the draft based on the lines of influence in the function of friction along the lateral surface and the resistance of the tip. R. Hefeli and H. Becher obtained an empirical dependence for determining the precipitation of single piles.

In Kazakhstan, a number of huge construction projects, such as high-rise building, freeway bridges across river or sea, high-speed railways, wind power plant, and harbor constructions, are in progress in urban and coastal areas. Deep foundations are frequently used in heavy load and large span projects. The high capacity of deep foundation, in combination with the high cost of top load systems providing over 12000 кН reaction loads, make conventional load testing too costly or impractical. For large capacity, the test can be conducted with bi-directional testing (O-cell testing (Osterberg 1984,). In this test, the load cell is hydraulically driven, high capacity, sacrificial jack-like device, installed within the foundation unit at the chosen location typically half way down the “capacity length” of the foundation in a manner in which the upper and lower portions of the foundation unit are tested against each other [7-14]. The Bi-Directional static load test by O-Cell, invented by Prof. Osterberg, is a hydraulically powered, sacrificial load cell that is installed within the test shaft. Hydraulic cables run up the pile, along the carrying frame, allowing the field crew to apply pressure and subsequently load the pile. Figure 1 is very similar to the setup used in this study, with exception to the rebar cage supporting the shaft. The principle advantage of the O-Cell setup is there are no requirements for a reaction system. The reaction occurs within the shaft, whereas the O-Cell begins to expand from applied hydraulic pressure as shown in Figure 1.

Level Reference	Level description	Depth, m (RL)	Depth, m
COL	Cut of Level	347.40	0.000
SG 1	Strain Gauges	346.90	0.500
SG 2	Strain Gauges	344.20	3.200
SG 3	Strain Gauges	341.50	5.900
SG 4	Strain Gauges	338.80	8.600
SG 5	Strain Gauges	336.10	11.300
SG 6	Strain Gauges	333.60	13.800
J 1	Hydraulic jack assembly (3 x 500tonnes)	330.60	16.800
SG 7	Strain Gauges	327.60	19.800
SG 8	Strain Gauges	323.90	23.500
SG 9	Strain Gauges	320.20	27.200
SG 10	Strain Gauges	317.40	31.000
PT	Pile Toe	316.90	31.500

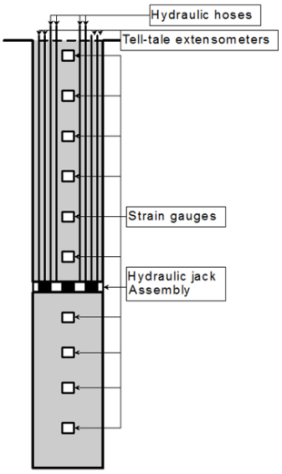

Fig. 1. Schematic Diagram of Pile Layout for Bi-Directional Load Test (BDSLT).

Using the conventional, top-down load test method, much larger loads would be required to mobilize the entire shaft, along with a very large reaction frame (including reaction beams and adjacent reaction piles).

Pavilion of Kazakhstan (Sphere) is the only building in the world, which is a sphere finished form with a diameter of 80 meters. Possessing unique design features, a given shape of the building, as well as the functions of the exhibition building, it serves as a prime example of the use of renewable energy sources at the same time. The site chosen to accommodate Expo-2017 Astana is located 8 km south of the old city of Astana and just 4 km from the new government block on the southern bank of the Ishim River. The exhibition area with a total area of 25 hectares is surrounded by a territory of 149 hectares, intended for housing residential and mixed buildings, auxiliary exhibition facilities and transport infrastructure. The total area of the Exhibition Area is 174 hectares [9-11].

2 Geotechnical Descriptions of Construction Sites

At the construction site, a complex of laboratory and field studies of the soil base was also carried out. Based on the field description of the soils confirmed by the results of cone penetration tests and laboratory tests, a division of the soils composing the site of prospecting for engineering-geological elements (EGE) in the stratigraphic sequence of their occurrence was carried out (see Figure 2 and Table 1).

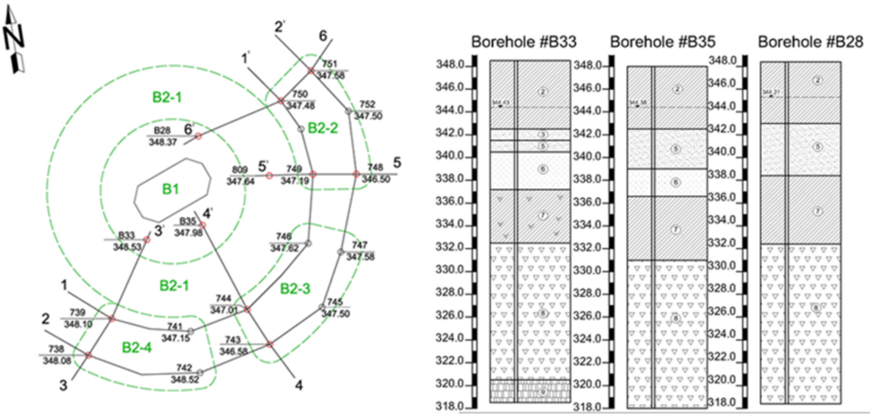

Fig. 2. Plan for the location of boreholes at the construction site (Build – B1) and EG cross section.

Table 1. The physical and mechanical characteristics of the soils in Expo-2017.

EGE	Soils	Design data soil soaking in natural state				
		E, MPa	**ρ, g/cm^3**	**c, kPa**	**φ_o**	**R_o, kPa**
2	Loams	12.5	1.91	38	19	-
3	Sands	17.0	1.92	2.0	35	-
5	Coarse sands	21.0	1.92	1.0	38	-
6	Gravel soils	23.0	-	-	-	300
7	Loams	14.0	2.04	27	27	-
8	Soils	36.4	-	-	-	400
9	Rock debris soils	36.4	-	-	-	450

R_o: Compression Strength

3 Brief characteristics of piles and location of pile foundations

Static testing with Osterberg method (O-Cell testing) was carried out for the test of deep foundations at the site of the construction of this object. Four bored piles were subjected to static tests (Bi-Directional Static Load testing by ASTM - 2 piles, Static Compression Load Test (SCLT) by ASTM – 1 pile and Static Load Test (SLT) by GOST-1 pile) (see Figure 3). The test pile was a 1000 mm diameter bore pile with 31.5m length. The target of this tests was obtaining of bearing capacity of piles on problematical soils ground of Expo 2017 using different test and standards. Shown in Figure 3 placement of tested piles according to the pile draft of Expo 2017 (B1): Pile A #106 (SCLT by ASTM); Pile B (O-Cell-1); Pile C (O-Cell -2); Pile D #166 (SLT by GOST).

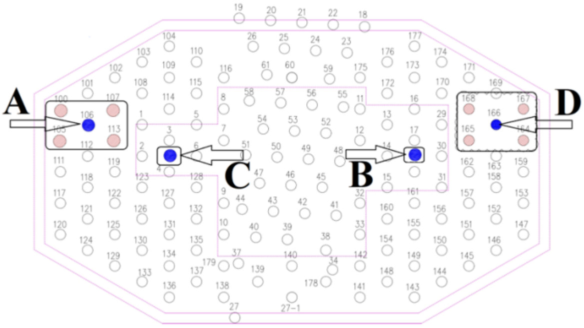

Fig. 3. Placement of tested piles site B1.

4 Methods for testing pile foundations for static load

4.1 Method of Static load test by GOST

Results of static tests of soils for bored piles carried out in accordance to GOST 5686-20 are shown below. Test was carried out after the pile concrete strength had attained more than 80% of the design value [6].

The measurement limits and division value of pressure gauges used to determine the load on the pile during testing are selected depending on the maximum load on the pile provided for by the test program, with a margin of at least 20 percent. Loading of the tested pile is carried out evenly, without impacts, in load steps, the value of which is set by the test program, but is taken no more than 1/10 of the maximum load on the pile specified in the program. When deepening the lower ends of full-sized piles into coarse-grained soils, gravelly and dense sands, as well as into clayey soils of a solid consistency, it is allowed to take the first three load steps equal to 1/5 of the maximum load indicated in the program. At each stage of loading a full-scale pile, reports are taken on all strain gauges in the following sequence: zero report - before loading the pile, the first report immediately after the application of the load, the field of this - four reports in succession with an interval of thirty minutes, and then every hour until conditional deformation stabilization. The criterion for conditional stabilization of deformation when testing with a full-scale pile is taken to be the pile settlement rate at a given stage of loading, not exceeding 0.1 mm over the last 60 min of observations, in the presence of sandy soils or clay soils from hard to hard-plastic consistency, they lie under the lower end of the pile, and if under the lower end of the pile, clay soils from soft-plastic to fluid consistency are covered, then two hours of observation. The load during testing with a full-scale pile must be brought to a value at which the total settlement of the pile is at least 40 mm. When deepening the lower ends of full-sized piles into densely broken, dense sandy and clayey soils of a solid consistency, the load must be increased to the value provided for by the test program, but not less than one and a half values the bearing capacity of the pile, determined by calculation, or the design resistance of the pile by material.

The pile is unloaded after reaching the maximum load with supports equal to double (in one step) values of the loading steps, with each step holding for at least fifteen minutes. Load cell reports are taken immediately after each unloading step and after fifteen minutes of observation. After complete unloading (down to zero), the elastic movement of the pile should be monitored for 30 minutes in sandy soils under the bottom end of the pile and 60 minutes in clay soils with recording every 15 minutes. During the testing process, a log is kept, and the results of testing soils with piles are drawn up in the form of graphs of the dependence of the pile settlement on the "load-settlement" load and the measurement of deformation over time at the stages of loading.

The load of the tested piles with static vertical-pressing forces, at the above EXPO-2017 construction site, was 12000kN (Figure 4). The calculated permissible vertical-punching load on the pile, taking into account the safety factor γ_k =1.2 according to paragraph 3.10 of SNiP RK 5.01-03-2002 "Pile foundations", it is recommended to take equal 10000 kN. Both results are shown in Figure 5 (SLT by GOST).

4.2 Method of Static Compression load test by ASTM.

Results of Static Compression Loading Testing was carried out in accordance to ASTM D 1143-07 (2013) is mentioned below. In the first cycle, the experimental pile was loaded to 6000kN of the design load, in the second cycle to twice the design load which is 12000kN.

The maximum load of the tested piles with from static vertical-pressing forces, at the above construction site, was 12000kN. It should be noted that even with a maximum test load of 12000kN, only the elastic operation of the pile in the ground is demonstrated, as evidenced by a slight residual soil settlement after unloading, which is approximately 1.4 mm. Both results are shown in Figure 4 (SCLT by ASTM).

The holding time of intermediate loading stages was 30 minutes and unloading approximately 20 minutes. The time for maintaining peak loads was 120 and 240 minutes (Figure 4). Figure 6shows the test arrangement for the static compression load test with the use of reaction pile to counterweight the load reaction to the pile.

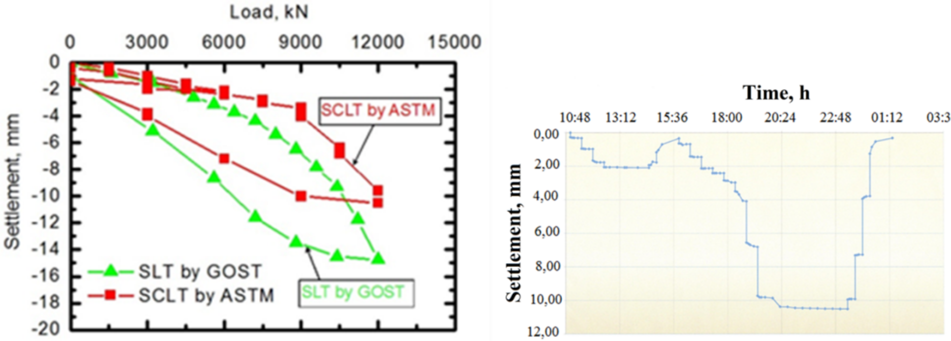

Fig. 4. Results of static loading tests (SCLT and SLT) from ASTM and GOST.

The working test pile is loaded up to 200% of the working load and settlements of the pile under various load steps recorded the settlements of 2.09mm (at 100% working load) and 10.51mm (at 200% working load). The values are observed to be within acceptable limits which was calculated as in equation (1) as mentioned in ASTM D1143-7(2013).

$$U_z = PL/AE + 0.01d \tag{1}$$

where,
Uz = Pile settlement
P = Load
L = Pile embedment length
A = Pile cross sectional area
E = Young's Modulus
D = Pile diameter
Uz = 12000 kN*31.5 m/((1.0)2*π/4) m2*(32*106)) kN/m2+0.01*1.0 m = 0.015+0.010 mm = 25 mm > 10.51mm.

Base on the calculation made for the particular pile, the allowable pile settlement is 25mm which is more the actual pile settlement of 10.51mm.

4.3 Method of Bi-Directional Static Load Test (BDSLT) by ASTM

Bi-directional load testing using Osterberg cells are now becoming common practice around the world or with combination of conventional load testing (Castelli 2002, 2004; Russo ;2003; Seol 2009; Fellenius 2010). The bi-directional load testing has been used since 1984 for drilled shafts piles and barrettes. This paper introduces engineering applications of bi-directional load testing in drilled shafts piles. In bi-directional load testing foundation are loaded by the embedded load cell. To determine the location of the load cell, soil investigation report has to be studied to work out the equilibrium point typically half way down the "capacity length" of the foundation. The load cell is loading equipment specially designed using built in hydraulic jacks, top and bottom plates etc. Pressure is applied to the load cell by high pressure hydraulic oil pump on the ground through the flexible oil hose embedded in the pile. The pressure in the load cell can be measured by manometer, and the displacements of the top, bottom plates and pile head can be measured by displacement transducers, the former two displacements of which is connected to the load cell by telltale wire rope in the embedded steel casings in the pile. When loaded, the load cell expands, pushing the upper shaft upwards and the lower shaft downwards, which would mobilize the side resistance and base resistance. According to relationship between the movement and the applied loads, the two P-S curves can be obtained. From the two P-S curves and their corresponding curves, bearing capacities of both upper and lower segment of the pile can be determined. The equipments used in drilled piles testing are shown in Figure 5. The bi-directional load testing is being used routinely in many parts of the world, especially in USA, Europan and West Asian with advantages of high loads, improved safety, economy, reduced work area. Testing has been made with load cell placed in various locations in deep foundation shown in Figure 11. Some tests could be the combination of bi-directional load test and conventional head-down test. The development and use the bi-directional load testing for the high capacity, static testing of piles gives engineers a new and powerful tool to evaluate the characteristics of piles.

4.3.1. Load test procedure (Bi-Directional Static Load Test)

Load testing commenced by applying hydraulic pressure to the hydraulic jacks using an air-driven hydraulic pump. A high-pressure Bourdon gauge as well as a calibrated pressure transducer was used to measure the pressure. The displacement transducers, which were supported from the reference frame, were used to measure relative movements at the designated points of measurement (Figure 5).

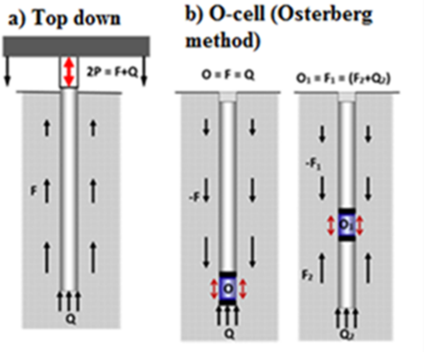

Fig.5. Scheme test load top downward and BDSLT.

It is to be noted that the loads applied by the bi-directional hydraulic jacks act in two opposite directions, resisted by upper side shear above the jack assembly and by the combined end bearing and lower side shear below the jack assembly.

A millimetre scale was fixed to the reference frame and direct readings from a dumpy level to this scale were observed to check that there were no errors in the displacement transducer readings.

The top and bottom of hydraulic jack assembly movements were measured using displacement transducers that were connected to telltale rods against the reference beam and the top of pile were measured using displacement transducers installed at the pile platform level. A total of Six (6) no's displacement transducers were used to measure all movements at the designated points. All the displacement transducers performed well during the duration of the test.

The equivalent top loaded load movement curves are derived. Adjustment for additional elastic compression is calculated as PL/EA where P is the applied load, L the length, E the elastic modulus and A, the cross-sectional area. The results show that the test pile would have an elastic settlement of 6.50mm at 14500 kN and 14.40mm at 29000 kN.

All Sister bar strain gauges installed were found to be in good working order throughout the duration of test. The displacement, load and strain data were automatically recorded at 1-minute intervals. In order to verify the compliance of the pile capacity, Osterberg method namely as Bi-directional Static Load Test (BDSLT) was use as shown in Figure 6. The distinctiveness of the O-Cell test method is that the load is applied not on the head of the pile, but in the body of the pile, where the jack (power cell) is installed, works in two directions. The power cell (O-Cell jack) divides the test pile into two parts: the upper (upper test element – UTE) and the lower (lower test element-LTE). The power cell (O-Cell jack) is a system of calibrated hydraulic jacks combined into one module.

Fig. 6. Bi-Directional static load test in construction site.

5 Results of the static load test on the pile

Figure 7 shows the results of strain-measuring transducers from the test. It presents the load distribution along the length of the piles and indicates the lateral resistance of the pile with respect to the depth. The graph shows that even at a maximum load, the pile is secured in position by lateral resistance of the subsoil. Only a small part of the load accumulates to the pile edge.

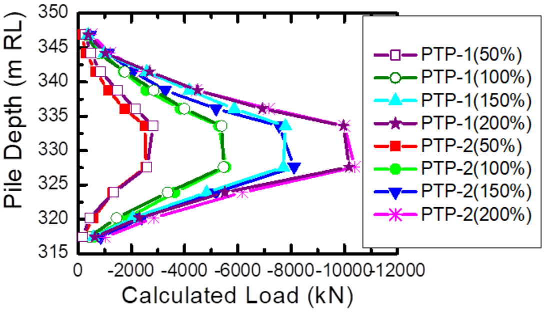

Fig. 7. Calculated load distribution of piles (BDSLT-1 and BDSLT-2).

In test pile with O-Cell-1 shear distribution located at the pile section above the jack, indicated an increase in unit skin friction from 76kN/m^2 to 481kN/m^2 at 200% of the working load. For section below the jack, the shear distribution indicated an increase in unit skin friction from 190kN/m^2 to 458kN/m^2 at 200% of the working load. Similarly, for test pile of O-Cell-2 the shear distribution located at the pile section above the jack, shows an increment in unit skin friction from 83kN/m2 to 477kN/m^2 at 200% of the working load. For the pile section below the jack, the shear distribution indicated an increase in unit skin friction from 207kN/m^2 to 437kN/m^2 at 200% of the working load. Both O-Cells test results are presented in Figure 7. At maximum test load of 100% (14500kN), the maximum displacements of the piles for BDSLT-1 are 7.30 mm and BDSLT-2 is 6.50 mm. At maximum working load of 200% (29000kN), displacements of the piles for BDSLT-1 and BDSLT-2 are 18.35mm and 14.40mm respectively (see Figure 8).

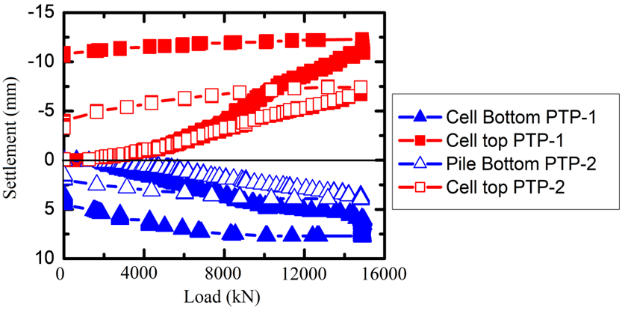

Fig. 8. Results of Bi-directional Static Load Test piles BDSLT -1 and BDSLT -2.

6 Discussion of the results obtained

Table 2 presents a numerical comparative analysis of the bearing capacity of piles, obtained by different methods in this research from Figure 9. It is shown in this figure, a comparison of the test results graphical curve obtained by the SCLT method and the equivalent "load-settlement" curve determined by the O-Cell method. For the comparative purposes a criterion of Pile A (SCLT by ASTM), Pile B (O-Cell-1), Pile C (O-Cell-2) and Pile D (SLT by GOST), a settlement of 10mm and 14 mm has been taken to denote the similarity of load capacity for all pile. These two values were chosen base on Kazakhstan technical specification on determining the limiting value of acceptable which is given as 16mm settlement for any loading.

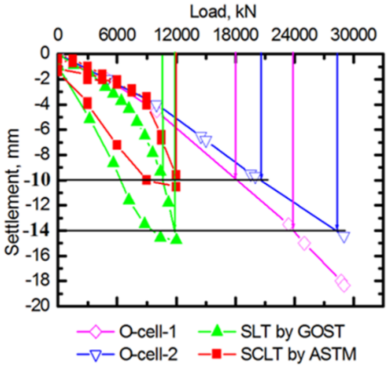

Fig. 9. Comparison of test results carried out by methods: SCLT, SLT and BDSLT.

Table2. Results of pile static load testing (SLT and SCLT)

PILE ID	**The results of fixed settlements of 10 and 14 mm has been taken**	
	10 mm Load (kN)	**14 mm Load (kN)**
Pile A (SCLT by ASTM)	11788	-
Pile B (BDSLT-1)	18220	23985
Pile C (BDSLT -2)	20535	28385
Pile D (SLT by GOST)	10630	11814
Pile A (SCLT by ASTM) / Pile D (SLT by GOST)	1.1 *	-

Pile C (O-Cell -2) / Pile B (O-Cell-1)	1.1 **	1.1 ***

Note:
- from “Pile A” maximum settlement - 10.51 mm;
* Coefficients (ratio) of fixed settlement of 10 mm has been taken (from Top down methods);
** Coefficients (ratio) of fixed settlement of 10 mm has been taken (from BDSLT method);
*** Coefficients (ratio) of fixed settlement of 14 mm has been taken (from BDSLT method).

7 Conclusions

This paper presented brief descriptions of innovation changes to the concept of Kazakhstan pile foundation design. The overlay of the curves showed that the similarity of the results base from the convergence of the graphs is observed only at the initial stage of loading. The value tends to diverge non linearly showing a change in the trajectory of the SCLT curve. The characteristic of the creeping stage of soil resistance, is observed from the SLT and SCLT tests. However, for the O-Cell curve (at this stage of loading) is more representing the characteristic of the elastic resistance of the soil. When testing piles using the SCLT method "from top to bottom", a design load of 6000 kN corresponds to a settlement of 2.09 mm and at a maximum test load of 12000 kN the settlement obtain is 10.51 mm. It should be noted that even with the maximum test load, only the elastic operation of the pile in the ground is revealed with a slight residual soil sediment after unloading with a magnitude of approximately 1.4 mm. When testing piles using the O-Cell test, a maximum test load of 29000 kN corresponds to a settlement of 18.35 mm for the O-Cell-1 pile and 14.40 mm for the O-Cell-2 pile. During the testing of the piles, both elastic and plastic deformation of the soil was observed due to the greater test load on the pile than experiencing in the SLT method.

Acknowledgements

This research has been funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP13268718).

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