Geotechnical Infrastructures of New Capital Astana on Problematical Soil Ground

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ABSTRACT
Just as every civilization in the history is originated from the riverside, so the city of Astana - new capital of Kazakhstan has been developed around the Ishim River. As its result,. there are many bridges across the river. Also high rise building such Palace of Peace, Khan Shatur, Abu -Dhabi Plaza, Ministry of Transporation Buildings, International Astana Airport, Mosque Hazret Sultan, New Railway Station, Expo2017 constructions site and other many structures founded in problematical soil ground of Astana. These unigue buildings need performing of deep driving and boring piling foundations. For designing of piling foundations on difficult soils are important investigations of behavior of piles by using of dynamic, static, O-cell, integrity piling tests. This paper includes of fresh results of several piling tests with comparison of numeral analysis by FEM. These investigations of interaction of piles with soil ground of new capital are important for understanding of mechanism of working of different piles on soft and hard soils of Astana. Also this paper introduced of experiences of piling constructions in winter season on freezing ground. The last page of paper includes recommendations and conclusion with proposing of methodic for the obtaining of bearing capacity and settlements of driving and boring piles on problematical soil ground of Astana.

Keywords: Bored piles, dynamic load test, static load test, rapid load test, O-cell testing.

1 INTRODUCTION

Nowadays many megaprojects are emerging in the new capital of Kazakhstan – Astana. The high rates of construction and appearance of high-rise buildings having modern architecture, and engineering megaprojects, led to a wide use of pile foundations.
Modern construction puts modern requirements in front of engineers and designers, and so instead of traditional decisions it came to the use of new economical and ecological efficient technologies such as CFA (continuous flight auger), DDS (drilling displacement system), steel "H" piles, and so on.
It is well known that pile foundation is one of the most widely used types of foundation at the construction sites of Kazakhstan.
Application of pile foundation is explained by necessity of ensuring a high bearing capacity for high-rise buildings.
During the last 15 years, many high-rise buildings supported by pile foundation are rising up in Astana, the new capital of Kazakhstan. Following megaprojects are already completed: Ministry of Transportation and Communication, Housing estate – Izumrudny Kvartal (Emerald square),

Cultural and Entertainment Center – Khan Shatyry and so on (Figure 1). Many megaprojects are under construction or in planning. One of the unique projects is the housing estate “Abu-Dabi Plaza” which started on 1 July 2011 in Astana. The project of housing estate was designed by famous architect Norman Foster. By preliminary evaluation, the cost of project exceeds 1.5 billion US dollars. This will be the highest building in Central Asia and ranked 14th in the world. "Abu-Dabi Plaza" - a complex from several towers, united around the main building with a height 382 meters - 88 floors (Figure 1).

Figure 1 Megaprojects of New Capital of Kazakhstan – Astana.

1.1 General aspects of Kazakhstan pile design concept

It has been mentioned previously that existing Kazakhstan standard documentation of pile design is out of date and does not meet the requirements of modern engineering. The standard needs to be revised. Nowadays, conception of pile foundation design is in the process of modernization, as presented in Figure 2.

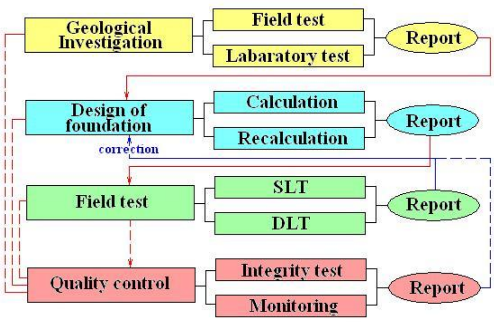

Figure 2 Pile foundation design concept.

Design of pile foundation includes two critical stage of analyses: bearing capacity and settlement analysis. The preliminary design is performed based on the engineering and geological investigation of construction site. Accuracy of pile design generally depends on the accuracy of data presented in geological report. Final pile design project is corrected after approval by field tests.

The preliminary configuration (length and cross section) of pile depends on required bearing capacity of pile and may be determined by following equation, recommended by Kazakhstan Standard:

$$F_d = \gamma_c\left(\gamma_{cR} R A + u \sum \gamma_{cf} f_i h_i\right) \qquad (1)$$

Where Y_c – safety factor; Y_{cR} and Y_{cf} – coefficients of soil work condition under the pile tip and surrounding of pile, respectively; R, f_i – soil resistance under the pile tip and shaft resistance respectively, kPa; A – cross section of pile, m^2; h_i – thickness of *i*-layer, m.

In this case, the results obtained by cone or standard penetration tests (CPT or SPT) and plate load test are more valuable, particularly to definition of shaft and tip resistance of soil.

Unfortunately, existing Standards do not take into account soil compaction under the high concrete pressure in case of CFA technology and soil displacement without excavation in case of DDS technology that lead to reduction of settlement and increase in bearing capacities of pile foundation (Sultanov at al, 2010). In connection with aforementioned, it is suggested to use following coefficients of soil working condition as presented in Table 1.

Table 1 Coefficient of soil work condition

Type of pile	Y_{cR}	Y_{cf}
Driving Pile	1,0	1,0
Boring Pile	0,7-1,0	0,7
DDS (FDP) Pile	1,3	1,0
CFA Pile	1,0	1,0

To accurately analyze the bearing capacity of CFA pile, it is necessary to take into account volume change of (∇ r) of borehole, by appearance in borehole additional pressure; with classical solution of Lambe based on theory of elasticity in linear formulation, as defined as (Ashkey, 2008):

$$\nabla r = \frac{(1+\mu)\cdot r \cdot \sigma_h^{concrete}}{E_h} \qquad (2)$$

where, μ - Poisson ratio of concrete (μ=0.20); r - normal pile radius; $\sigma_h^{concrete}$ - lateral stress of concrete to soil; E_h - Young modules considering soil layer for horizontal deformation, kPa.

Predictable settlement is performed by «method of layer-wise summation» (word-for-word). The general principle of this method is definition of settlement in limited compaction zone by following equation, recommended by Kazakhstan Standard:

$$S = \frac{\Sigma\sigma_{zp}^{avr}\cdot\beta\cdot h_i}{E_i} \qquad (3)$$

where σ_{zp} – stress in soil due to loading, kPa; *β* – coefficient depending on radial expansion of soil; h_i – height of i- layer of soil, m; E_i – Young modulus of *i*- layer of soil, kPa. Compaction zone is conditionally equal - when stress from weight of soil quintuple more than stress from pile load. In this case accuracy of Young modulus is very important. Young modulus may be determined by laboratory or field test. It is suggested to use Young modulus with allowance of depth of load application as defined after SLT. The principle of this method is assuming pile as plate (Yenkebayev, 2008). Young modulus may be defined by following equation:

$$\mathbf{E} = \frac{\left(\mathbf{F_d}/\mathbf{A}\right)\cdot\mathbf{d}\cdot\mathbf{K_0}}{\mathbf{S}}\cdot\frac{\omega\grave{}_{avr}}{\omega_{avr}} \qquad (4)$$

where F_d – bearing capacity of pile obtained by SLT of pile, кN; $\mathbf{A}$ – cross section of pile, m2; $\mathbf{S}$ – settlement of single pile by SLT; ω_{avr} – parameter depends on relative thickness of compaction layer ($\gamma = \mathbf{H}/\mathbf{b}$) and relationship semi-length of foundation to the semi-width ($\alpha = a/b$). ω'_{avr} - same parameter in case of unlimited thickness of compaction layer.

Generally this method is used for predicting settlement of pile-raft foundation by SLT of single pile. Settlement of piled-raft foundation defined by aforementioned «method of layer-wise summation». Recently forecast by FEM analysis has become more acceptable. FEM allows relatively reliable analysis of pile settlement and bearing capacity in a short time. However, application of FEM analysis is confined by absence of requirements in existing Kazakhstan Standards. Results of FEM analysis depend on calculation model. In case of correct approach FEM analysis gives very satisfied convergence. Example of comparison results of FEM and SLT of CFA pile is presented in Figure 3, using the numerical approach proposed by Prof. Tadatsugu Tanaka. The first diagram shows result of incorrect FEM analysis, second shows FEM analysis taking into account expansion of pile due to of high pressure of concrete. The FEM mesh and average expansion of pile body depending on soil strength is also presented in Figure 3.

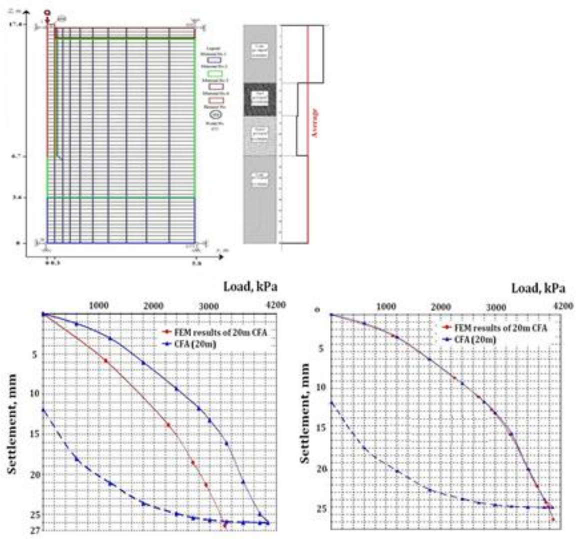

Figure 3 FEM analysis of CFA pile

2 FIELD TEST OF PILE FOUNDATION

2.1 Dynamic load test (DLT)

DLT is a fast bearing capacity analysis field test and give more or less reliable value of pile bearing capacity. For definition of the bearing capacities of piles, it is required to

use average refusal which are obtained during redriving of the piles after their "rest". The rest time depend on soil condition of site: for clayey soil 6 -10 days, for sandy and gravel soils up to 3 days.
Bearing capacity of the piles is defined by following empirical equation:

$$F_u = \frac{\eta AM}{2}\left[\sqrt{1+\frac{4E_d}{\eta AS_a}\cdot\frac{m_1+\varepsilon^2(m_2+m_3)}{m_1+m_2+m_3}}-1\right] \qquad (5)$$

where η=factor, dependent on concrete strength of the piles; A=cross section of tested pile; M=1 – factor, dependent on pile driving hammer's impact; E_d =effective energy of blows of the hammer, kNm.
According to Kazakhstan Standard at least 6 piles must be tested by DLT on each construction site (Fig. 4).

Figure 4 Photo and schema of dynamic load testing in Kazakhstan.

2.2 Static Load Test (SLT)

SLT one of the more reliable field tests in analyzing pile bearing capacity. SLT should be carried out for driving piles after the "rest" and for bored piles after achievements of the concrete strength, by more than 80%.
According to requirements of Kazakhstan Standard - SNiP RK 5.01-03-2002 – ultimate value of settlement of the tested pile is determined as   and depending on category of construction is equal to 16 or 24 mm. The last argument shows conditional character of SLT method.
According to Kazakhstan Standard 1% of constructed piles on construction site must be tested by SLT, but at least 2 SLTs in a site must be done (Fig. 5).

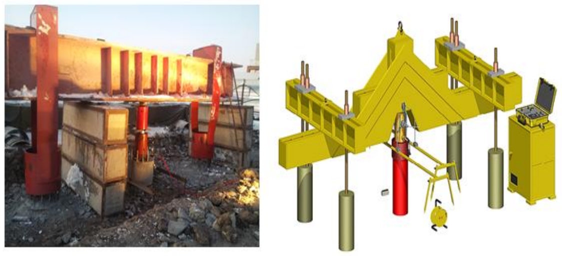

Figure 5 Photo and schema of static load testing in Kazakhstan.

2.3 Comparison of SLT and DLT

SLT and DLT both are practised in Kazakhstan construction. According to experience on construction sites of Astana, some difference exists between SLT and DLT results. Moreover, results of bearing capacity of pile depend on type of hammer. Thus, DLT results obtained by using hydro-hammer are more approximate to the SLT results, namely more reliable than results obtained by using diesel-hammer (Seidmarova, 2008). The safety factor as defined by comparative analysis of many DLT and SLT data is presented in Figure 6.

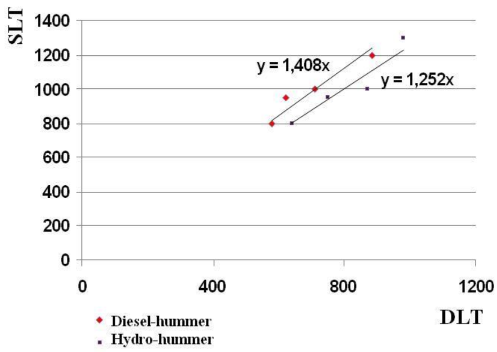

Figure 6 Comparison results of DLT and SLT.

2.4 O-Cell test or static testing of subsoil by the piles with bidirectional load

The target of this tests was obtaining of bearing capacity of piles on problematical soils ground of Expo 2017 (Astana, Kazakhstan).
The method suggested by George Osterberg allows determining the calculated subsoil resistance under the lower end of the pile and on its lateral surface at the same time. The specific thing of the O-Cell test is that the load is applied not on the pile head, but on the pile body where the adjustable jack is set. It works in two directions. Hydraulic

adjustable jack is installed at the depth of 2/3 pile length - 16.8m (Fig. 7).
The test pile was a 1000 mm diameter bored pile. The hydraulic jack assembly comprising of three (3) 500-tonne capacity bi-directional hydraulic jacks, was in-stalled at 16.80m (330.60 m RL) below the Cut off Level (Fig. 7).
The hydraulic jack assembly and steel cages were jointed and lowered into the bored hole. The pile was concreted according to the contractor’s method statement (Fig. 8).
There were a pair each of tell-tale rod installed at the top and the bottom of the hydraulic cell assembly. Their movements were measured against a reference frame constructed by the contractor.

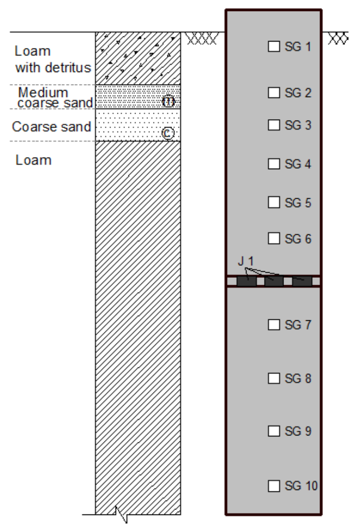

Figure 7 Geotechnical condition and details of piles in construction site of EXPO-2017 (Astana).

Ten levels of vibrating wire-type strain gauges (Geokon- 4911 Sister bar type) comprising four units at each level were installed in the test pile to measure strain at nominated locations. The strain gauges were mounted at designated Level 1 to Level 10 as(SG1 to SG10) shown in the pile layout provided (Fig. 7).

Figure 8 O-cell tests of piles.

Before the tests 10 strain-measuring transducers connected to a data detector (data-logger) were installed in the body of the experimental pile. Unlike a traditional static testing, O-Cell allows to obtain two dependences "load- subsidence": one curve characterizes the resistance of the pile under the bottom end, the second one – on its lateral surface. Therefore, using these two curves we can obtain an equivalent curve "load-subsidence", which is analogous to the curve SLT.
The O-Cell test results are presented in figure 9. At the maximum test load of 100% (14500kN), the maximum displacements of the piles are PTP-1 – 7,30 mm and PTP-2 – 6,50 mm, and at the maximum workload of 200% (29000kN), displacements of the piles are PTP-1 – 18,35 mm, and PTP-2 – 14,40 mm. Figure 9 shows the comparison of the results of piles test by O-Cell method (the equivalent curve).

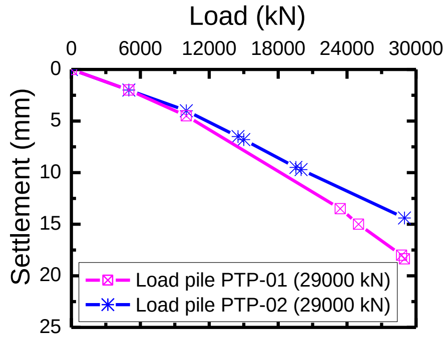

Figure 9 Results of the test O-Cell.

2.5 *Alternative Load Test Method*

From aforementioned it follows that SLT and DLT both have disadvantages. SLT required a lot of time, works and cost. Prescribed by Standard quantity of required SLT is not enough to adequately realize soil condition of construction site (2 SLT for 200 piles only). DLT is much faster but is not so reliable and is applicable to driving piles only.
Today, in process of adaption into Kazakhstan practice is an alternative load test method which precluded disadvantages of both SLT and DLT – Rapid Load Test (RLT). RLT allow performing up to 10 piles per day and much cost effective than SLT (Zhussupbekov and Matsumoto, 2011). The comparison of SLT and RLT as obtained by Matsumoto are presented in Figure 10 that shows reliability of RLT.

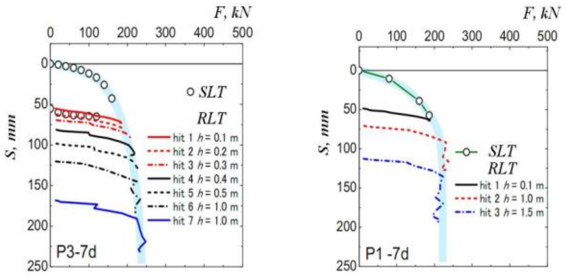

Figure 10 Results SLT and RLT.

3 QUALITY CONTROL OF PILE FOUNDATION

3.1 Pile Integrity Test (PIT)

Pile integrity test is one of the non-destructive methods of pile quality control. This method allows analyzing integrity control for all existing types of piles (boring, injection, driving and so on). PIT is base on wave propagation theory in rigid body and is concerned with one of the modern quality control methods used world-wide. PIT allows detecting pile defects: approximate pile length, expansion and narrowing of pile cross section, modification of soil layers, heterogeneity of pile material, cracks in cross section of pile, extrinsic material in pile body (Fig. 11).

Figure 11 Photo and schema of pile integrity testing in Kazakhstan.

Advantages of PIT are as follows: portable device is easy to carry. One operator will be able to test over 100 piles per day, depends on site condition, pile head preparation and approach to the pile; minimum influence to the construction work on the site; significant defects may be detected in the beginning of the construction. PIT has some limitations: reflection of the bottom of pile sometimes has errors depending on soil condition; little deflection (less than 5 %) of pile cross section cannot be identified.

According to Kazakhstan Standard requirements it is necessary to test 60% of boring piles and 50% of driving piles.

3.2 Geomonitoring

Geomonitoring for foundation settlement is one of the quality control methods that can be carried out during and after construction in exploitation period. Monitoring is indirect control of pile installation evaluation.
The principle of this method is monitoring the settlement of special marks which are installed to interested points of construction. Monitoring starts from the beginning of construction and allows revealing defects of foundation installation.
Result of monitoring for settlement development during construction of «Ministry of Transportation and Communication » building is presents in Figure 12.

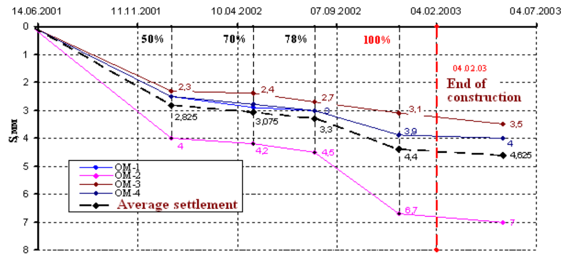

Figure 12 Geomonitoring results.

3.3 Analysis of effect of pile driving on the existing foundation (vibration monitoring)

The article presents the results of the analysis of the effect of vibration exposure pile driving on the existing foundations of a functioning oil and gas complex located in Tengiz city (Fig. 13). The aim of the tests (vibration monitoring) was to determine the smallest allowable distance piling devices excluding the impact of vibration on the foundation and ensuring the safe operation of the plant. The article presents the results of vibration exposure piling at different distances from the base, taking into account the natural oscillations of technological processes, solid foundation and others, as well as the results of excitation of ground

mass at various distances from the source of vibration exposure (pile driving).
The source of the vibration excitation was pile driving (C16-40) through pile-driving equipment Banut 555 with a mass of hydraulic hammer 6,075 tonnes and a maximum drop height 1.0 m. In case of driving of piles was drawn up the statement of pile-driving. Vibromonitoring was carried out by the instrument Profound VIBRA +, with use of the 3D seismic sensors. The interval of measurement of vibration was carried out every 5 seconds. Tests were executed according to requirements of norm of DIN 4150-3 according to which the most allowed level of vibration is equal 5,00mm/sec. (from 0-10 Hz).
The maximum impact on a soil array was recorded at a distance 40m from a source in case of driving of piles No. 3, 5 and 6. In all cases the maximum values of speed of oscillations were recorded when dipping C16-40piles on depth from 5 to 8 m.

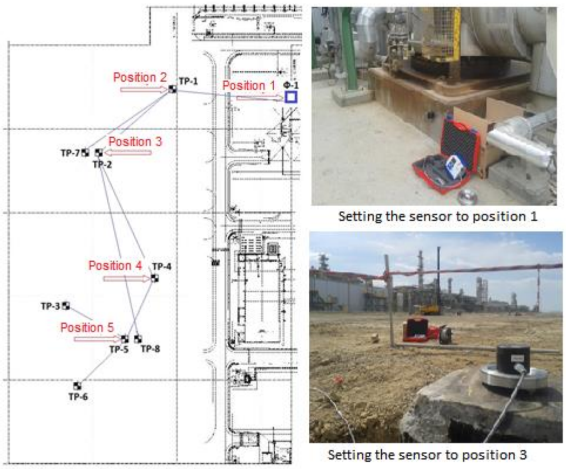

Figure 13 Vibration monitoring at the Tengiz oil and gas facilities

4 CONCLUSIONS

Existing pile foundation Standards practiced in Kazakhstan are out-of-date and are in urgent need for modernization. This paper presented very short descriptions of coming changes to the concept of Kazakhstan pile foundation design.
Presented aspects of modern pile technology design, including FEM analysis, allow making more reliable prediction of bearing capacity and settlement of pile that has become very important for the preliminary design of piling foundation projects. RLT allows performing up to 10 piles per day, much cost effective than SLT, and more authentic than DLT. RLT is a type of DLT and is appropriate for any type of pile, but cannot be used to full extent on construction sites of Kazakhstan due to absence of Standard.
Pile integrity test is in the process of gaining official acceptance in Kazakhstan. PIT is a non-destructive method allowing quality control of pile body whereupon of pile installation and even after many years of building exploitation. Geomonitoring for foundation settlement is indirect control of pile quality evaluation method and has become more relevant, especially for high-rise building construction.
The main advantages of O-Cell method are good applicability for the piles of great length and diameter, especially in cramped conditions; the possibility of pile loading by heavy loads with the increasing the number of adjustable jacks; improving the accuracy of the results due to the absence of pile heave because the anchoring system is not applied; the improvement of safety due to the absence of the reaction system on the ground level and the energy of testing load develops at a sufficient depth.
There is no necessity for engineers to rely on the test piles reduced in scale due to the very high cost of testing of the piles of a large diameter using traditional methods.
The development of bidirectional load on high bearing capacity of the piles gives engineers a new powerful tool for assessing the characteristics of the piles with the subsoil. Along with this we can say that using this method saves funds and time. It is because there is no necessity to use anchoring piles.
Along with the benefits of tests there are some limitations. The applied method is mainly used for bored piles, just as adjustable jack and transducer for measuring displacements have to be pre-installed before testing and after testing they remain in the pile.
Along with the disadvantages, the major advantage of the O-Cell is that it can help to

determine the calculated resistance of subsoil under the lower end of the pile and on its lateral surface, which is of special value for the analysis and evaluation of bearing capacity of piles of a large diameter.

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