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COMPARATIVE ANALYSIS OF NUMERICAL MODELING AND STATIC PILE LOAD TEST RESULTS FOR CFA PILES

CFA ҚАДАЛАРЫН САНДЫҚ МОДЕЛЬДЕУ НӘТИЖЕЛЕРІН ЖӘНЕ СТАТИКАЛЫҚ СЫНАУ ЖҮКТЕМЕЛЕРІМЕН САЛЫСТЫРМАЛЫ ТАЛДАУ

СРАВНИТЕЛЬНЫЙ АНАЛИЗ РЕЗУЛЬТАТОВ ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ И СТАТИЧЕСКИХ НАГРУЗОК ИСПЫТАНИЙ СВАЙ CFA

Abstract. *The goal of this paper is a comparative assessment of results obtained from the field static pile load test and simulated numerical analysis. Plaxis 3D Foundation software was used to simulate the field static pile test for numerical analysis. Results of this study demonstrate the comparison of load-settlement curves obtained from field static pile test and numerical analysis of CFA pile. As a result of field static pile load test, the bearing capacity of the pile was determined. Moreover, results of residual settlement after unloading in case of the field test and numerical analysis were demonstrated. As a result of the load-settlement curve, numerical analysis with Plaxis 3D software is applicable for pile design with sufficient accuracy. The study emphasizes the importance of validating CFA pile behavior through both empirical and computational approaches in challenging geotechnical conditions. This dual-method approach helps improve the accuracy of pile foundation design and ensures better reliability of structural performance. The correlation between measured and simulated results allows engineers to verify modeling assumptions and boundary conditions. Additionally, this approach offers a cost-effective solution in large-scale construction projects where field testing every pile is impractical. Ultimately, the integration of field testing with advanced numerical modeling supports optimization in foundation engineering and contributes to safer and more efficient construction practices.*
Keywords: *static pile load test, CFA, load-settlement curve, numerical analysis, Plaxis.*

Аңдатпа. *Бұл мақаланың мақсаты – статикалық қадаларды далалық сынау және имитациялық сандық талдау нәтижесінде алынған мәліметтердің салыстырмалы бағасын беру. Plaxis 3D Foundation бағдарламалық жасақтамасы сандық талдау үшін далалық статикалық сынауды модельдеуге қолданылды. Зерттеу нәтижелері CFA қадалары үшін алынған жүктеме-отырғызу қисықтарын далалық және сандық әдістермен салыстыруды көрсетеді. Далалық статикалық сынақ нәтижесінде қаданың жүк көтергіштігі анықталды. Сонымен қатар, жүктемені түсіргеннен кейін қалдық отыру шамалары сандық және далалық әдістермен салыстырылды. Бұл қисықтарды сараптау Plaxis 3D бағдарламалық қамтамасымен жүргізілген талдаудың қадаларды жобалауға жеткілікті дәл екенін көрсетеді. Бұл зерттеу күрделі топырақ жағдайында CFA технологиясының сенімділігін тексерудің маңыздылығын көрсетеді. Эмпирикалық және* *модельдік әдістерді біріктіру инженерлік шешімдердің дәлдігін арттырады. Модельдеу мен шынайы өлшеу нәтижелерінің сәйкестігі инженерлерге бастапқы шарттар мен жүктеме әсерлерін дұрыс орнатуға мүмкіндік береді. Бұл әдіс ірі құрылыстарда уақыт пен ресурстарды үнемдейді. Далалық сынақ пен сандық модельдеуді үйлестіру құрылыс іргетастарының сенімділігі мен тиімділігін арттыруға ықпал етеді.*

Түйін сөздер: *статикалық қада жүктемесін сынау, CFA, жүктемені реттеу қисығы, сандық талдау, Плаксис жүйесі, инженерлік-геологиялық түсірістер, арнайы геотехникалық карталар.*

Аннотация *Целью данной статьи является сравнительная оценка результатов, полученных в результате проведения полевого статического испытания сваи и численного моделирования. Программное обеспечение Plaxis 3D Foundation использовалось для моделирования полевого испытания с целью проведения численного анализа. Результаты исследования демонстрируют сравнение кривых осадок под нагрузкой, полученных в полевых условиях и в результате численного анализа CFA-сваи. В ходе испытания была определена несущая способность сваи, а также проанализированы остаточные осадки после разгрузки по обоим методам. Полученные результаты подтверждают, что численное моделирование с использованием Plaxis 3D может быть эффективно применено для проектирования свай с достаточной точностью. Работа подчёркивает значимость комплексного подхода, объединяющего экспериментальные и цифровые методы анализа свайных фундаментов в сложных инженерно-геологических условиях. Сопоставление результатов способствует повышению достоверности расчётов и позволяет более точно интерпретировать поведение свай под нагрузкой. Кроме того, такой подход экономически эффективен при массовом строительстве, когда проведение испытаний каждой сваи невозможно. Интеграция полевых и численных методов позволяет оптимизировать проектные решения и повысить надёжность и безопасность строительных объектов.*

Ключевые слова: *статическое испытание сваи на нагрузку, CFA, кривое распределение нагрузки, численный анализ, Plaxis.*

Introduction. Pile foundations are critical to ensuring the stability and longevity of construction projects, especially for multi-story buildings on challenging engineering and geological soils. Determining the bearing capacity of piles and their load response with precision is essential for both safety and cost optimization.

CFA piles are a type of cast-in-place pile constructed in a single continuous cycle. The technology, illustrated in Figure 1, involves advancing a hollow-stem auger to the required depth, during which the soil retained on the auger flights provides lateral support to the borehole walls. As the auger is withdrawn, concrete is pumped through the hollow stem under pressure, maintaining the stability of the surrounding soil through positive concrete pressure. Immediately after completing the concreting process, reinforcement is inserted into the fresh concrete, providing additional structural strength.

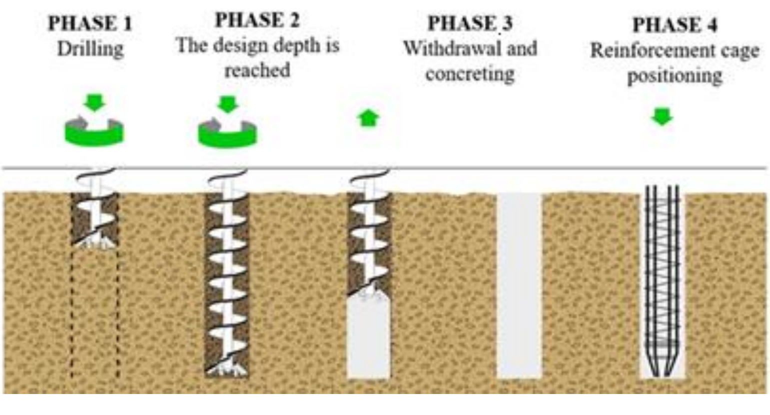

Figure 1. Sequence of CFA pile installation

Note – compiled by the author

However, when using such innovative methods, especially in the absence of experience or data for similar geological conditions, static pile testing becomes a mandatory step for quality control

(Brinch, 1970; Chin, 1970; Meyer, Siemaszko, 2019). These tests help confirm the reliability of the applied technology and ensure that the piles meet the design specifications.

Eurocode EC7-1 (Section 7.5) (British Standards Institution, 2004) outlines several scenarios in which pile testing is considered necessary, including the use of new methods or the lack of sufficient theoretical foundation. The works of Bergado (Bergado et al, 1996) and Farouk (Farouk, Shahien, 2013) indicate that the behavior of piles in such conditions can differ significantly from theoretical calculations, particularly when high groundwater levels are present.

The experience of countries with rapidly developing construction markets, such as the UAE, also underscores the importance of using CFA technology (Farid, 2023). According to local regulations, 5% of piles are randomly tested, and an integrity test is performed on all piles (The Code Handbook, 2013). Static tests, in which the load is increased to 1.5-2 times the design load, allow for the evaluation of pile behavior under load and help prevent costly mistakes.

For the construction of a multi-story building in Al-Arasaat district, Baghdad province, a decision was made to conduct tests on a working CFA pile to confirm its design parameters. Research shows that CFA piles have several advantages, including high installation speed and reduced vibrational impact on the surrounding environment (Shah, Deng, 2020; Fetherston et al., 2019); however, their behavior under load requires detailed analysis. According to the works of De Beer (DeBeer, 1968) and Fellenius (Fellenius, 1968), these approaches have proven to be reliable tools for evaluating ultimate axial load and interpreting the load-settlement curve.

Considering the above aspects, conducting static pile tests with the CFA method in complex soil conditions requires the use of reliable methods for assessing their bearing capacity. Both conventional field static test and modern numerical analysis methods, which have proven effective in engineering practice, were applied.

2 Methods. 2.1 Field static pile load test Field static pile load test. Continuous Flight Auger (CFA) technology was chosen to improve the properties of soft soils. This method involves rotating a hollow auger with a diameter of 600 mm to a depth of 18 m, during which concrete of grade C25/30 is pumped through the auger under constant positive pressure. The concrete pouring helps strengthen the soil as it hardens. When extracting the auger, vertical pressure is applied to the soil, while horizontal pressure is exerted on the surrounding soils, thereby improving their physical and mechanical properties. Therefore, the pile installation process not only strengthens the soil but also creates a solid foundation for further testing and evaluation of the pile's bearing capacity.

Tested CFA pile PCFA54 is one of the piles of a piled raft foundation of the planned 18 floors building and placement of the analyzed pile is shown in Figure 2.

Figure 2. Testing pile PCFA54 installed with CFA method

Note – compiled by the author

The next important stage of the study is the assessment of the pile's bearing capacity, which is carried out through static load testing (SLT). After the piles were installed using the CFA technology, it is necessary to confirm their calculated capacity to withstand load in real operating conditions. The field static pile load test was carried out on 18-19 April, 2022. The working load for each pile is 150 tons, while the maximum test load is 225 tons. The tests were conducted in two loading cycles, each consisting of several steps with progressively increasing load. These cycles help model various operating conditions for the piles, aiding in the precise evaluation of their behavior under different load values and interaction with the soil. A detailed description of the loading cycles and corresponding stages is provided in Table 1.

Table 1. Loading Cycles and Parameters for Static Load Testing (SLT)

Cycle	Load cycle (%)	Load value (tons)	Minimum load holding time	Accumulated time (min)
1	0	0	0	0
	25%	37.5	30 min	30
	50%	75	30 min	60
	75%	112.5	30 min	90
	100%	150	1 hour	150
	75%	112.5	10 min	160
	50%	75	10 min	170
	25%	37.5	10 min	180
	0	0	1 hour	240
2	100%	150	6 hour	600
	125%	187.5	1 hour	660
	150%	225	6 hour	1020
	125%	187.5	10 min	1030
	100%	150	10 min	1040
	75%	112.5	10 min	1050
	50%	75	10 min	1060
	25%	37.5	10 min	1070
	0	0	1 hour	1130=18 h 50 min

Note – compiled by the author

To ensure the accuracy and stability of the tests, the Kent ledge reaction system is used. This high-tech system was chosen for its reliability and its ability to minimize external influences, such as vibration or soil displacement. A detailed schematic representation of the static pile load test is provided in Figure 3, which illustrates the setup and configuration of the system. The reaction system includes piles installed at least 2 meters below the base of the test pile to minimize errors during testing. The spacing between the centers of the reaction piles must be at least 3 meters, equivalent to four times the diameter of the test pile, in compliance with Eurocode EC7-1 and British standards. This spacing ensures no interaction between the piles, thereby maintaining the accuracy of the results.

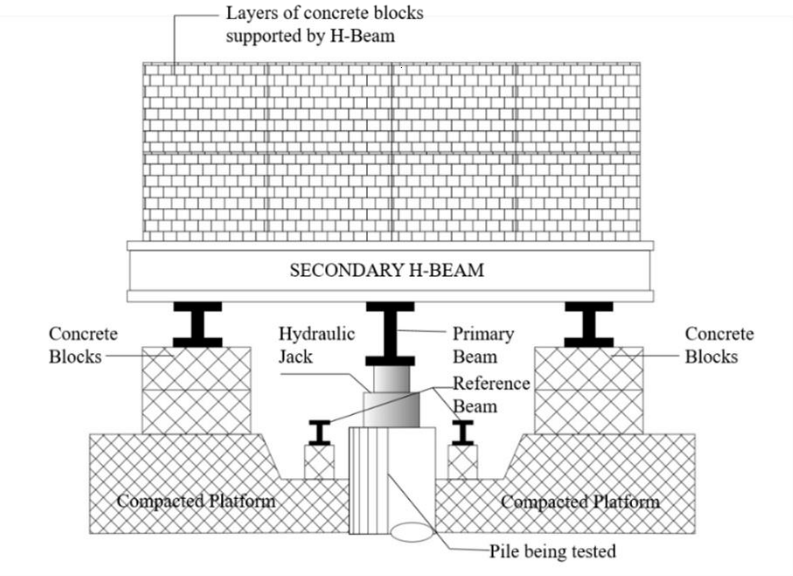

Figure 3. Static pile load test

Note – compiled by the author

For the accuracy of measurements during the tests, calibrated and certified manometers are also used, as well as dial gauges to determine the pile settlement. These devices record changes in load and settlement in real-time, allowing the pile behavior to be closely monitored. The testing was executed using hydraulic jack, pressure gauge of 600 bars and two dial gauges in accordance with B.S. Standard Test Methods for "Deep Foundations under Static Axial Compressive Load" and were shown in Figure 4. A continuous recording of the pile head displacement in every addition or lifting of load within the specified time period was recorded.

Figure 4. Dial gauges' readings during 150 Tons load test

Note – compiled by the author

2.2 Numerical analysis with Plaxis 3D Foundation software. The numerical analyses were conducted using the commercial software Plaxis 3D Foundation. The software allows to use advanced constitutive models. The Mohr-Coulomb material model was used in this analyses for soil layers and data used for soil properties was taken from the results of geological survey. Soil parameters such as Young's modulus (E), Poisson's ratio (ν), cohesion (c), internal friction angle (φ), and dilatancy angle (ψ) were required for this model and given in table 2. The model boundaries of the research area were 30 m in a horizontal and 30 m in a vertical direction and the geological conditions of the tested area are demonstrated in Figure 6. The upper layer of Silty Clay with a thickness of 9.25 m followed by 16.25 m of Silty Sand. A thin layer of Silty Clay with thickness of 4.5 m is located 25.5 m below the surface. A groundwater level was determined at 4 m below the surface.

The CFA pile was modeled using the Linear Elastic (LE) material model. The body of the CFA pile was modeled as a cluster with the dimensions of the radius and pile length of 0.6m and 18m, respectively. On top of the pile a distributed load of 225 tons was placed. Considering the recommendations of the Plaxis manual, the extended interface was modeled below the pile's base (Holʼko, Stacho, 2014). Initial geological conditions and CFA pile creation were simulated in the first construction stage and second stage, respectively.

3. Results and Discussions. 3.1 Field static pile load test. Static pile load test was carried out in the period of April 18 through April 19, 2022 after 24 days of casting piles. Bored pile with length of 18 m and 600 mm diameter installed by CFA method. In order to assess static pile load test results pile bearing capacity is determined from pile-head load-settlement curve. These data were collected during the field test on pile PCFA 54 (shown in Figure 3) included strains and top load. Figure 5 demonstrates static loading test results of pile-head load plotted against the pile settlement.

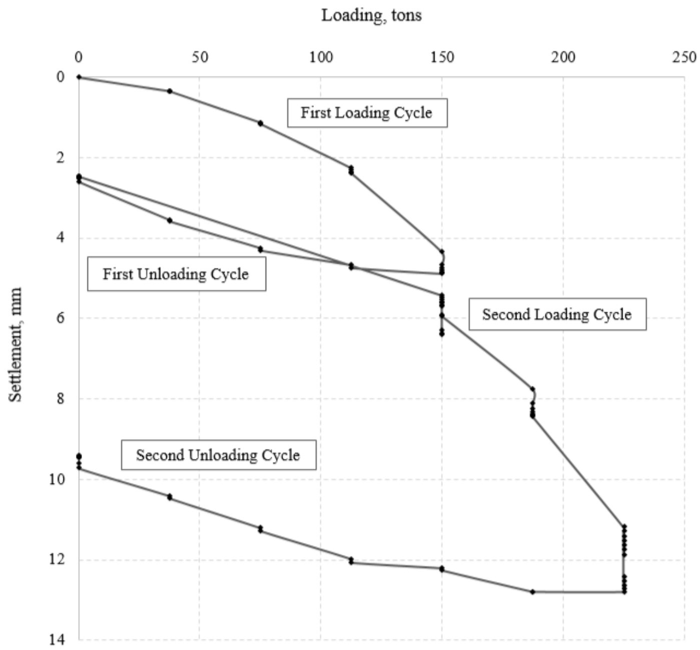

Figure 5. Pile-head load-settlement curve for pile PCFA 54r

Note - compiled by the author

The total settlement in first cycle was 4.88 mm under 150 tons, which is working load, while the final residual of settlement for first cycle was 2.46 mm which is equal to 50% of total settlement. The total settlement was 12.79 mm under 225 tons load equal to 150 % of the working load in second cycle, while the final residual of settlement for second cycle was 9.40 mm, which is more than 50% of total settlement equal to 73 %.

As stated in the standards of Federation of Piling Specialists in British Standards, bearing capacity of the pile is accepted as pile toe resistance at the settlement of 10% of pile diameter (Shanz et al., 1999). The tested pile did not show in all stages of test any unnatural behavior up to applying of loads 225 tons with average total settlement was 12.79 mm, which is within the permissible limits of settlement. Consequently, the results indicate that total settlement of 12.79 mm represents approximately 2.13 % of pile diameter, which is less than 10% threshold, falling within the standard limits.

Since the total settlement in 100% of the adopted design load is equal to 150 Tons not more than 10 mm > 4.88÷5.93 mm in two cycles, and then it is accepted by the criteria of standards. Consequently, this tested pile No. PCFA- 54 with 600 mm diameter is adequate to design load equal to 150 Tons.

3.2 Numerical analysis with Plaxis 3D Foundation software. The numerical analysis was performed in order to understand the results of real field static pile load test data and to improve the results interpretation of the pile load test. Geotechnical model of pile and geology of the area of interest is shown in Figure 6.

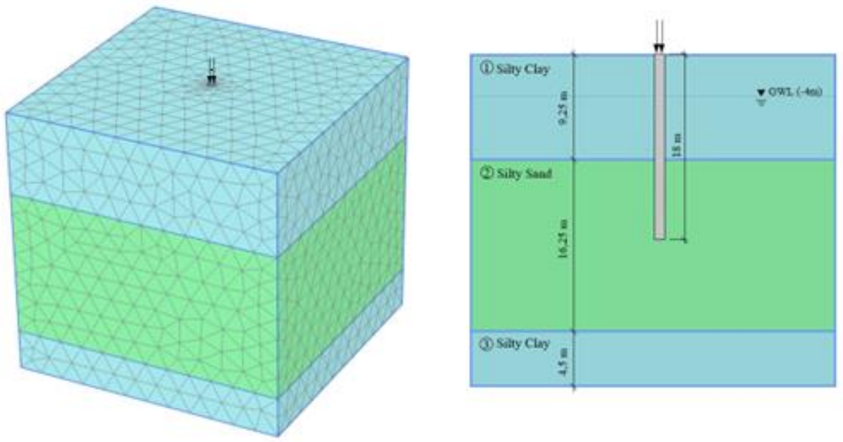

Figure 6. Numerical model of the analyzed CFA pile: overall view and profile of the model
Note – compiled by the author

Linear elastic non-porous model with following properties was chosen for concrete pile material: unit weight 24 kN/m^3, reference modulus of elasticity E_{ref}=30GPa and Poisson's ratio υ=0.2. Basic soil properties of geological conditions are demonstrated in Table 2.

Table 2. Basic soil properties for numerical model

Name	Soil type 1	Soil type 2	Soil type 3	Pile (Concrete)
Symbol	Silty Clay	Silty Sand	Silty Clay	-
Depth (m)	9.25	25.50	30.00	18.00
Thickness (m)	9.25	16.25	4.5	18.00
γ (kN/m^3)	19.50	24	19.50	24.00
γ_{sat} (kN/m^3)	21.00	25	21.00	-
φ'	22	35	22	-
c'	23	19	23	-
E	20000	75800	20000	30*10^6
υ	0.3	0.4	0.3	0.2
Note – compiled by the author				

The results of the Plaxis 3D software numerical analysis were presented in Figures 7-8 in terms of total principal stress and total displacement. According to the previous studies, the groundwater level was modeled 4m below the surface using a generated phreatic level in numerical modeling (Hyodo et al., 2020). The groundwater was modelled regarding to the actual engineering-geological conditions of the tested area. Maximum value of total principal stress was equal to 0.01066*10-12 kN/m2 on element number of 1307 at Stress point 5227, while minimum value was equal to 5236 kN/m2 on element 4410 at stress point 17640. Maximum value of total displacement (u) at 150 Ton was equal to 5.456 mm.

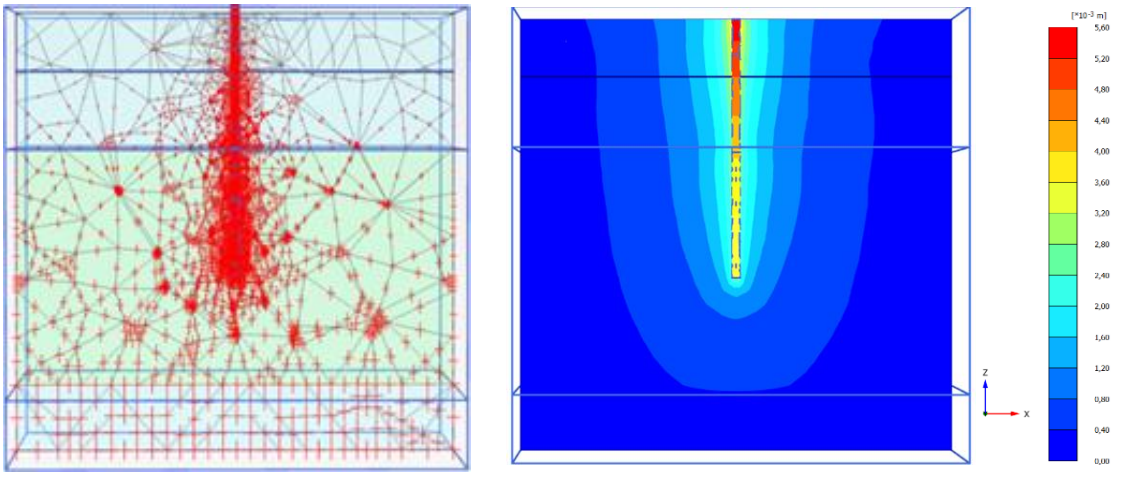

Figure 7. Total principal stress and total displacement at 150 Ton
Note – compiled by the author

Maximum value of total principal stress was equal to 260,3 kN/m2 on element number of 4495 at Stress point 17980, while minimum value was equal to -7855 kN/m2 on element 4410 at stress point 17640. Maximum value of total displacement (u) at 225 Ton was equal to 15.22 mm.

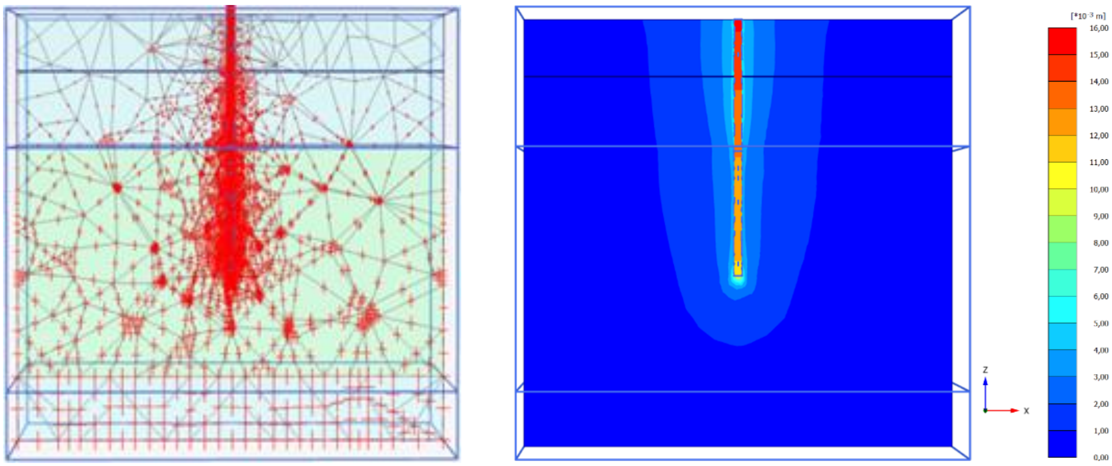

Figure 8. Total principal stress and total displacement at 150 Ton
Note – compiled by the author

Results of actual field static pile test and numerical analysis were compared and demonstrated in the load-settlement curve in Figure 9.

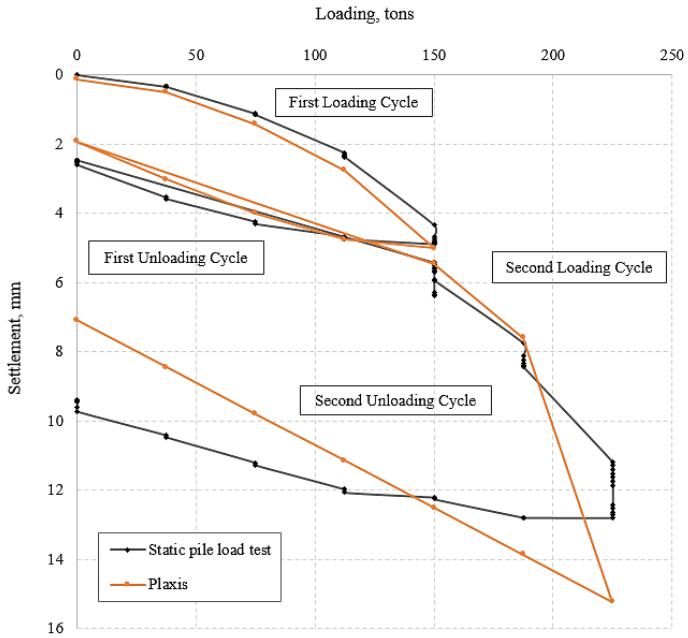

Figure 9. Compared load-settlement curve obtained from results of field static pile test and numerical analysis

Note – compiled by the author

*Conclusion***.** Conventional bored pile and CFA piles are commonly used worldwide. The CFA technology shows effectiveness in terms of time, cost and noise management. In this paper, the authors aim to assess if the findings obtained from field static test correspond with conclusions derived from numerical analysis. The numerical analysis was conducted by simulating field static pile test in Plaxis 3D Foundation software according to finite element method.

Results of this study demonstrates comparison of load-settlement curves obtained from field static pile test and numerical analysis of CFA pile. As a result of field static pile load test, bearing capacity of the pile was determined as pile toe resistance at the settlement of 12.79 mm which is less than 10% of pile diameter, while settlement results obtained from numerical analysis at 225 tons was equal to 15.22 mm, which is less than 10% of pile diameter as well. Even though results of residual settlement after unloading in case of the numerical analysis demonstrated less value than the settlement obtained from field test due to modeling assumptions of Plaxis, the results of the compared load-settlement curve show that numerical analysis with Plaxis 3D software is applicable for pile design with sufficient accuracy.

References

Brinch Hansen, J. (1970). A revised and extended formula for bearing capacity. Danish Geotechnical Institute, Bull, Copenhagen. 222-226

Chin, F. K. (1970). Estimation of ultimate load of piles not carried to failure. Proceedings 2nd Southeast Asia Conference on Soil Engineering, 81–92.

Meyer, Z., and P. Siemaszko. (2019). Static load test analysis based on soil field investigations. Bull. Pol. Acad. Sci.: Tech Sci. 67(2), 329–337.

British Standards Institution (2004). EN 1997-1:2004. Eurocode 7: Geotechnical Design – Part 1: General Rules. Code of Practice. BSI, London.

Bergado D., Anderson R., Miura N., and Balasubramaniam A., (1996). Soft ground improvement in lowland and other environments, ASCE Press, USA, 186-232.

Farouk A., and Shahien M., (2013). Ground improvement using soil–cement columns: Experimental investigation, Alexandria Engineering Journal, Vol. 52, Issue 4, 733 740.

Farid Ibrahim, Abdelkareem Alzo'ubi, Hamad Odhabi, (2023). A Generalized Regression Neural Network ModeltoPredict CFAPiles Performance Using Borehole andStatic LoadTest Data, Arabian Journal for Science and Engineering, 4403-4419.

The Code Handbook (2013). Abu Dhabi International Building Codes, Department of Municipal Affairs, Abu Dhabi, UAE.

Shah, F.R. and Deng, L. (2016). Comparing Axial Behaviour of Non Displacement and Displacement Piles using Field Load Tests, 69th CGS Conference Vancouver, B.C. Canada

Shah F., and Gurpersaud N., (2020). The application and development of Continuous Flight Auger (CFA) piles in the Prairies, Geo-Virtual conference Resilience and Innovation, Canada.

FetherstonJ., FlynnR. and ChongW., (2019). Lateral soil displacement resulting from the installation of CFA piles in soft marine clays, 13th Australia Zealand conference on Geomechanics, Acosta-Marinez and Lehane (Rds.), Australian Geomechanics Society, Sydney, Australia, 427-432

DeBeer E. E. (1968). Proefondervindlijke bijdrage tot de studie van het grensdraag vermogen van zand onder funderingen op staal. Tijdshift der Openbar Verken van Belgie, No. 6, 1967 and No. 4, 5, and 6.

Fellenius B. H. (2001). What capacity value to choose from the results a static loading test. We have determined the capacity, then what?, Two articles reprinted from Deep Foundation Institute, Fulcrum, Winter 2001, 19-22

Hoľko M., Stacho J. (2014). Comparison of numerical analyses with a static load test of a continuous flight auger pile, Slovak Journal of Civil Engineering, Vol. 22, No. 4, 1-10, https://doi.org/10.2478/sjce-2014-0017.

Shanz, T., Vermeer P.A., Bonnier P.G. (1999). The hardening soil model: Foundation and verification. Beyond 2000 in computational Geotechnics – 10 years of Plaxis, Balkema, Rotterdam, ISBN 90-5809-040-X.

Hyodo J., Tamari Y., Sone A., Ozutsumi O., Ichii K. (2020). A simplified method to consider the pile of insufficient length to obtain the support from bearing stratum, Journal of Asian architecture and building engineering, https://doi.org/10.1080/13467581.2020.1764847.

Krasiński A., Wiszniewski M. (2017). Static load test on instrumented pile –field data and numerical simulations, Studia Geotechnica et Mechanica, Vol. 39, No. 3, https://doi.org/10.1515/sgem-2017-0026.

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