WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.147653

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 4 2023

© 2023. Paweł Więcławski, Adam Krasiński.

pp. 157 –170

This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (CC BY-NC-ND 4.0, https://creativecommons.org/licenses/by-nc-nd/4.0/), which permits use, distribution, and reproduction in any medium, provided that the Article is properly cited, the use is non-commercial, and no modifications or adaptations are made.

Research paper

FEM modelling of screw displacement pile interaction with subsoil

Paweł Więcławski[1], Adam Krasiński[2]

Abstract: Predicting the Q–s settlement characteristics of piles is an important element in the designing of pile foundations. The most reliable method in evaluating pile-soil interaction is the static load test, preferably performed with instrumentation for measuring shaft and pile base resistances. This, however, is a mostly post-implementation test. In the design phase, prediction methods are needed, in which numerical simulations play an increasingly popular role.

This article proposes a procedure for numerically modeling the interaction of screw displacement piles with soil using the ZSoil 2D FEM program. The procedure takes into account technological characteristics of this type of pile, such as the process of soil expansion during the screwing-in of the auger and the pressure of concrete mix after pile concreting. They significantly affect the soil stress state, which is a key parameter for the pile load capacity. Geotechnical parameters of the subsoil were adopted from CPTU probing and laboratory tests. Due to the physical complexity, a constitutive soil model "Hardening Soil" (HS) was used in the analyses. The modeling procedure was calibrated on the basis of the static load test results of several instrumented piles, which were carried out as part of the "DPDT-Auger" research project. As a result of these calibrations, generalized recommendations were derived for an entire single pile modeling process with the axisymmetric system of ZSoil program. These can be useful in the reliable FEM prediction of the Q–s characteristics for screw displacement piles for practical engineering purposes.

Keywords: screw displacement piles, pile settlement characteristic, numerical simulations, finite element method, ZSoil

[1]PhD., Eng., Gdansk University of Technology, Faculty of Civil and Environmental Engineering, ul. Narutowicza 11/12, 80-233 Gdańsk Wrzeszcz, Poland, e-mail: pawel.wieclawski@pg.edu.pl, ORCID: 0000-0002-8681-7083
[2]University Prof., PhD., Eng., Gdansk University of Technology, Faculty of Civil and Environmental Engineering, ul. Narutowicza 11/12, 80-233 Gdańsk Wrzeszcz, Poland, e-mail: adam.krasinski@pg.edu.pl, ORCID: 0000-0002-8635-0241

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

1. Introduction

In deep foundations, displacement piles are a popular and still developing technique. This is a group of technologies in which the main idea is to make piles without soil excavation. Based on PN-EN: 1997-1: 2008 [1], one of the subgroups of this technology are displacement piles created by screwing holes with specially designed expanding augers. These are installed into the ground without casing. The expansion of the soil, mainly horizontal, causes compaction in the immediate vicinity of the pile, the increase of soil pressure and possible generation of water pressure in the soil pores. The diameters of such piles usually range from 300 to 400 mm, and their length does not usually exceed 16–18 m. The piles characteristically have good load-bearing capacities and moderate settlements [2], but they require drilling machines with significant torque due to high resistance in strong and stiff subsoil layers. This technology is also used in rigid column ground improvement.

In 2019–2022, the "DPDT-Auger" research project was implemented by the consortium of Gdansk University of Technology and Budokop Geotechnika contractor. The main goal of the project was to test and implement a prototype pile auger (DPDT), patented in Poland in 2020 [3]. Project No. POIR 04.01.04-00-0124/18 was co-financed by the Polish National Centre for Research and Development and EU funds. The operation and efficiency of the DPDT auger were tested in model and field tests and compared with typical displacement augers, mainly SDP (Fig. 1) [4].

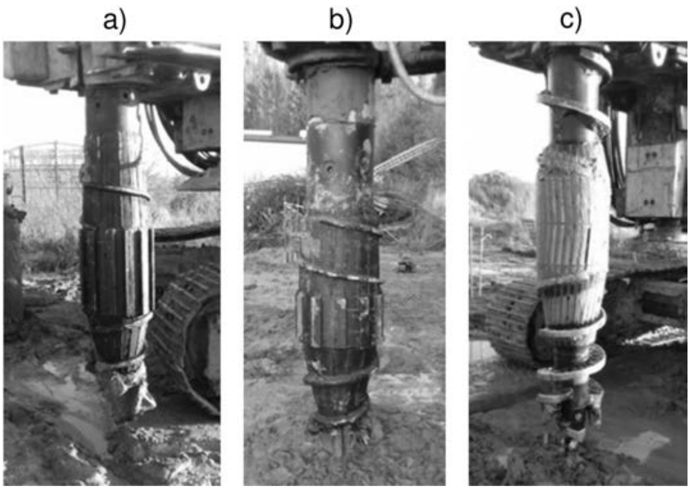

Fig. 1. Displacement augers tested in the research project: a) DPDT, b) DPDT-S (short), c) SDP, [4]

An additional goal of the project was to develop methods for calculating, forecasting and designing screw displacement piles, including numerical simulations with popular FEM programs. This article describes a proposal for a numerical simulation with the ZSoil program [5–8], due to the demand from practice and a small number of publications on screw displacement pile modeling in this program.

MOST WIEDZY Downloaded from mostwiedzy.pl

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

FEM numerical modelling of pile-soil interaction has been the subject of numerous scientific publications in recent years. In case of single piles, such simulations are carried out in an axisymmetric system, in which reliable results require taking into account the effects of pile installation. It is relatively simple to numerically simulate the installation of a bored pile, which was presented, among others, by Krasiński and Wiszniewski, [8]. Simulations of displacement piles are more difficult. Successful numerical simulations of precast driven, vibro-driven and jacked piles have been carried out in the Abacus program, e.g. Mahutka et al. [10] and Henke and Grabe [11]. In the case of screw displacement piles, one of the first numerical analyses was done by Basu and Prezzi [12] but it was limited to the problem of contact between a narrow non-cohesive soil section and the shaft of the displacement auger and pile. A proposal for modeling the installation and interaction of a screw displacement pile with non-cohesive soil in Plaxis 2D was also presented by Krasiński [13]. A slightly different approach to the simulation of the soil expansion phase concerning the volume strain option for SDP and CFA piles was also presented by Krasiński and Kusio [14]. In turn, numerical analyses of displacement pile installation in cohesive soil using the Abacus program were presented by Konkol [15]. Numerical simulations of pile installation and interaction with the soil can also be found in the work of Cudny [16].

2. FEM numerical simulation of piles using the ZSoil program

2.1. General rules for modeling

The following describes attempts to simulate the interaction of screw displacement piles with soil during a static loading using the numerical finite element method (FEM) in the standard geotechnical program ZSoil, version 2018. In order to obtain reliable results, the simulations included and reproduced the elements of pile installation technology that significantly affect interaction with soil and the load capacity of piles [2, 12, 13, 15]. The task was considered as an initial-boundary problem modeled in an axisymmetric system. The whole process of formal preparation and modeling should be carried out in accordance with rules given in ZSoil program manual [5–8]. The pile was expressed as a volume element (area with a width equal to the pile radius – $D/2$). In order to more precisely divide the area into finite elements, a denser finite element mesh was applied within 0.8 to 1.0 m around and under the pile, in which the elements had shapes similar to squares. In other areas, larger elements of rectangular, square or trapezoidal shapes were used (Fig. 2).

Contact elements (interfaces) were used along the pile-soil contact line (on the shaft and under the pile base). These elements have typical soil strength parameters, but they are also defined by the penalty normal stiffness multiplier K_{n_mult} and the ratio between the tangential and normal penalty stiffnesses K_t/K_n. The values of these two parameters were adopted in accordance with ZSoil recommendations [5] and on the basis of calibration

MOST WIEDZY Downloaded from mostwiedzy.pl

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

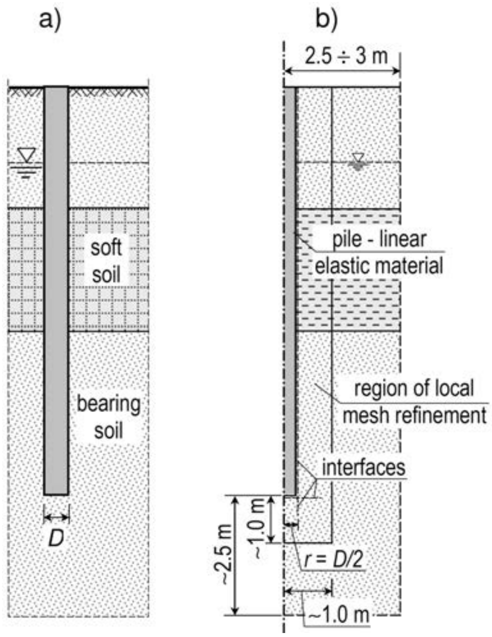

Fig. 2. Geometry and scheme of pile and soil discretization in the axisymmetric ZSoil system

tests. Interface elements were also used in the ground on the extensions of the vertical and horizontal pile base edges [13]. This enabled the obtaining of the effect of mutual soil mass shifts and a reduction of the unreal stress concentration under the pile base edge. In the geometric model, a stratification of the subsoil was set and adjusted to the geotechnical profile on the basis of the CPTU probing. The level of the ground water table was also taken into account. Due to the significant complexity of physical phenomena (loading, unloading and reloading phases), the Hardening Soil (HS) [8, 17] a constitutive model was used. The parameters of individual layers were obtained from laboratory tests (TX and oedometer) and in situ tests (mainly CPT) using Robertson classification [18].

The predicted Q–s characteristics of the pile design should take into account long-term conditions, which is why the calculations were made with drainage regardless of soil type (cohesive or non-cohesive). Generally, the purpose of the FEM numerical tests was to discover whether it was possible to reproduce numerically the behavior of screw displacement piles in the ground, and also whether it is possible to predict the Q–s characteristics of piles in medium-advanced FEM calculation geotechnical programs for design purposes.

2.2. Modeling of installation phases and pile loading

In order to obtain reliable mapping and calculation results, numerical simulations had to take into account elements of pile installation technology, which significantly affect their interaction and load capacity in the ground. In case of screw displacement piles,

MOST WIEDZY Downloaded from mostwiedzy.pl

www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

this mainly concerns soil expansion during auger drilling and pile concreting. During the first simulation attempts, the influence of pile installation effects was tested. Also various methods were tested to simulate the effect of soil expansion around the pile and the effect of concrete mix pressure on the soil. It was found that omitting the effect of soil expansion by the auger in numerical simulations causes significant underestimation of the calculation results. On the other hand, omitting the effect of concrete mix pressure after soil expansion phase causes the overestimation of calculation results. Then, the technological elements should be necessarily and properly modeled in phases preceding the final phase of pile loading. The calculation process of the screw displacement pile comprised the following phases:

1. Phase 0 – initial state.
2. Phase I – soil displacement by the auger.
3. Phase II – pile concreting (concrete mix pressure).
4. Phase III – insertion of pile with full strength and stiffness.
5. Phase IV – pile load test.

In initial stage (Phase 0), the original state of geostatic stress in the soil is determined. Depending on the soil origin, normally consolidated (OCR = 1.0) or overconsolidated (OCR > 1.0) soils should be assumed. Here, normally consolidated soils were assumed and hydrostatic ground water pressure in the subsoil.

The effect of auger soil expansion (Phase I) can be obtained by the axisymmetric expansion of the cylindrical cavity [19]. A similar modeling method was used in Plaxis 2D simulations, which were described in [13]. An alternative, substitute simulation method of soil expansion and stressing phase is the "volume strain" method used and described, for example, in Krasiński and Kusio [14]. As an expansion result, the effect of initial stress increase and pre-consolidation of the soil around and under pile base is obtained, which has a large impact on the results of further calculations. In ZSoil, it is most convenient and advantageous to model soil expansion by prescribed displacements, which is the closest to the real phenomenon. This is based on assigning radial horizontal displacements u_x in nodes at the pile hole wall and vertical displacements u_y in nodes at the bottom of the hole. These displacements are set in the "boundary conditions" option (tab). The soil material must simultaneously be removed from the pile domain.

In the calibration analyzes described below, the displacements u_x and u_y were selected by trials (with values of about 20–50 mm) to obtain a result as close as possible to the result of a real pile load test (Q–s characteristics).

As the auger is screwed out, surrounding soil moves radially back towards the hole, partially reducing its diameter. However, the hole is simultaneously filled with the concrete mix fed under pressure, which supports the soil walls. As a result, the hole does not close, but stress state changes occur in the soil surrounding the hole – the value of the horizontal stress component in load-bearing soil layers usually decreases, but it may increase in weak layers. After the auger is completely unscrewed, and even more after the vibrating of the reinforcement, the excess concrete mix pressure set by the pump is reduced to a value close to hydrostatic pressure. Then, as a result of water outflow from mix into the ground and the concrete setting and shrinking, the value of this pressure is further

Downloaded from mostwiedzy.pl MOST WIEDZY

www.czasopisma.pan.pl PAN www.journals.pan.pl

reduced. The technological phase of filling the hole with a concrete mix (Phase II) was modeled using radial stress p_x for inside pressure on the hole walls and vertical stress p_v for pressure on the bottom of the hole. In the proposed procedure, the assumed stress values (loads) p_x and p_y were reduced to 75% of fresh concrete mix hydrostatic pressure [5, 8]. The concrete mix pressure was additionally reduced by groundwater hydrostatic pressure, as it should have an effective value. The above described technological phases and their modeling methods are shown in Fig. 3.

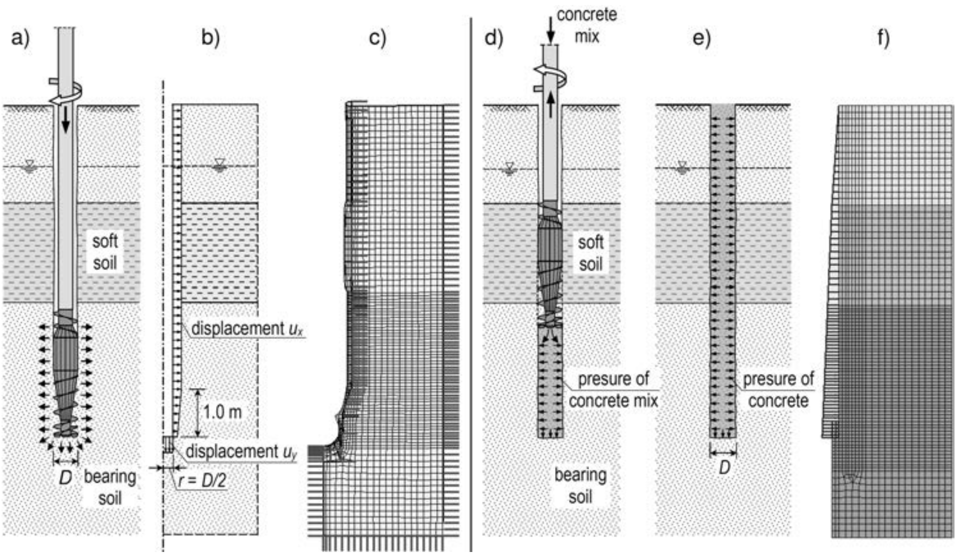

Fig. 3. Phases of pile installation. Phase I – auger soil expansion: a) real system, b) physical model for simulation, c) mesh deformation after displacement excitation; Phase II – pile shaft concreting: d), e) real phenomenon, f) simulation in ZSoil

Phase III modeling – insertion of the pile – was intended to introduce elastic material with hard concrete parameters (full stiffness and strength) into the pile hole. The linear elastic material model with the following parameters was used for concrete: $\gamma_b = 25$ kN/m^3, $E = 25$ GPa and $\nu = 0.167$. In the same phase, contacts (interfaces) on the pile shaft and under the base were activated. Simultaneously, the pile material was inserted and the p_x and p_y loads simulating concrete mix pressure were deactivated. During Phase III, there are no significant changes in the stress state and strain of the surrounding soil.

The final simulation stage was to model the pile load test (Phase IV), which was performed by applying a vertical load of evenly distributed $p_{Q,y}$ on the pile head. The value of this load was determined by trial and error so as to obtain a vertical pile displacement of about 10% of the pile diameter D or until the ultimate limit state was reached.

In addition to physical phenomena modeling, in ZSoil, the time operation intervals of these processes should be modelled by means of "existence functions" and "load functions". Functions related to this task are shown in Fig. 4 and 5.

MOST WIEDZY Downloaded from mostwiedzy.pl

www.czasopisma.pan.pl www.journals.pan.pl

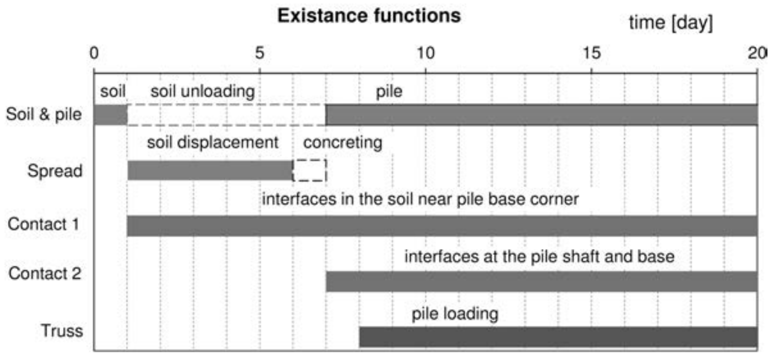

Fig. 4. Existence functions for particular stages of the analysis

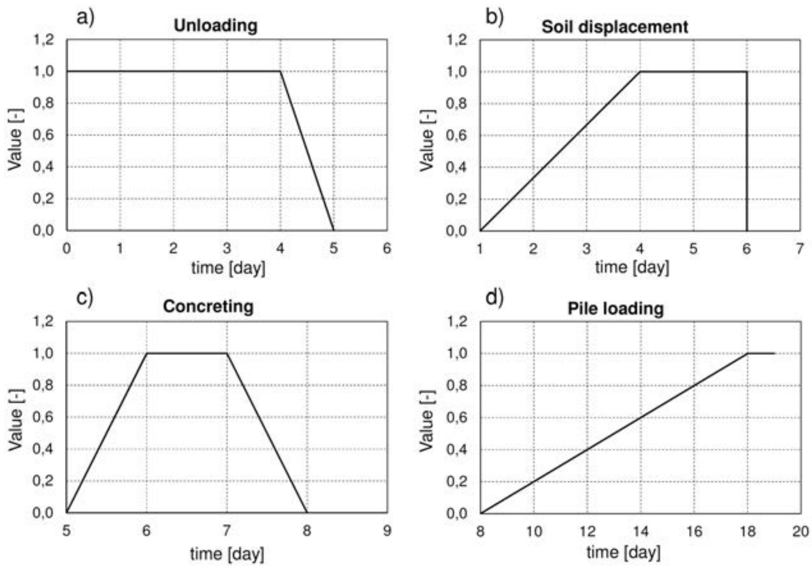

Fig. 5. Load functions for particular stages of the analysis: a) removing soil from the pile hole (unloading), b) auger expanding the soil; c) pile concreting (concrete mix pressure), d) pile static loading

3. Calibration of numerical model based on field test results

This chapter presents examples of numerical simulations results for 2 piles tested on experimental field plots in two different locations and in different ground conditions [4]. More simulations were carried out to calibrate numerical schemes and derive general rules for reliable prediction simulations.

MOST WIEDZY Downloaded from mostwiedzy.pl

With regard to the soil expansion phase, the prescribed displacement method presented above was used in all cases. In the case of the first pile test, extensive results were presented in the form of mesh deformations and stress maps from subsequent simulation phases, together with the final Q–s diagrams. With regard to the second pile test, for the sake of this article, only comparative charts of Q–s characteristics from the numerical simulation and the real test are presented. In ZSoil, as in other software, the calculation results can be generated, for example, in the form of mesh deformations in individual phases, maps of displacements, stresses, water pressures, etc. The obtained numerical values can also be viewed directly and/or downloaded. The hidden fictitious rod method ("Truss") was considered the most advantageous in determining the load-settlement (Q–s) diagram of the pile, both with regard to the total (Q_c–s), as well as the soil bearing layers (Q_N–s), the shaft (Q_s–s) and its base (Q_b–s) [9, 10]. Such a rod was placed in the pile axis (axis of the axisymmetric system) in the geometric model building phase. The rod had its cross-sectional parameter EA reduced 1000 times in relation to that of a real pile. Such a low axial stiffness practically did not affect the results of the numerical calculation. After performing the calculations, the numerical values of the fictitious rod axial forces and displacements were extracted from the post-processor and exported to an Excel sheet to create the Q–s characteristics of the pile. During these processes, the force values had to be multiplied by 1000.

3.1. Pile 602 from test plot 3

The simulation example concerns pile 602, DPDT with diameter $D = 0.40$ m and length $L = 10.5$ m [4]. The initial geotechnical parameters of the soil layers are listed in Table 1. The results of the numerical tests in the form of mesh deformation images and effective stress maps from the main simulation phases are shown in Fig. 6 and 7, and the Q–s plots compared with the real pile field test are presented in Fig. 8.

Table 1. Initial parameters of soil layer adopted for numerical analyzes of pile 602, [4]

Soil layer	Soil type	Unit weight		Friction angle	Cohesion	Dilatancy angle	Stiffness modulus			Poisson's ratio	Reference pressure	Modulus exponent
		γ	γ_{sr}	φ'	c'	ψ	E_{50}^{ref}	E_{oed}	E_{ur}^{ref}	ν	p_{ref}	m
		[kN/m^3]		[°]	[kPa]	[°]	[MPa]			[–]	[kPa]	[–]
(I)	grSa	19.0	20.0	40.0	0.0	8.0	50.0	50.0	100.0	0.2	100.0	0.3
(II)	Cl	19.5	19.5	30.0	5.0	0.0	5.0	5.0	10.0	0.2	100.0	0.9
(III)	FSa	19.5	19.5	35.0	0.0	3.0	25.0	25.0	50.0	0.2	100.0	0.3
(V)	siSa/Or	19.8	19.8	33.0	0.0	2.0	7.0	12.0	18.0	0.2	100.0	0.85
(VII)	siSa	19.9	19.9	37.5	0.0	5.0	14.0	17.0	30.0	0.2	100.0	0.7
(VIII)	Mud	17.8	17.8	37.0	6.4	0.0	2.1	2.1	6.0	0.2	100.0	0.9
(IX)	MSa	20.1	20.1	39.0	0.0	6.0	40.0	21.0	80.0	0.2	100.0	0.3

MOST WIEDZY Downloaded from mostwiedzy.pl

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

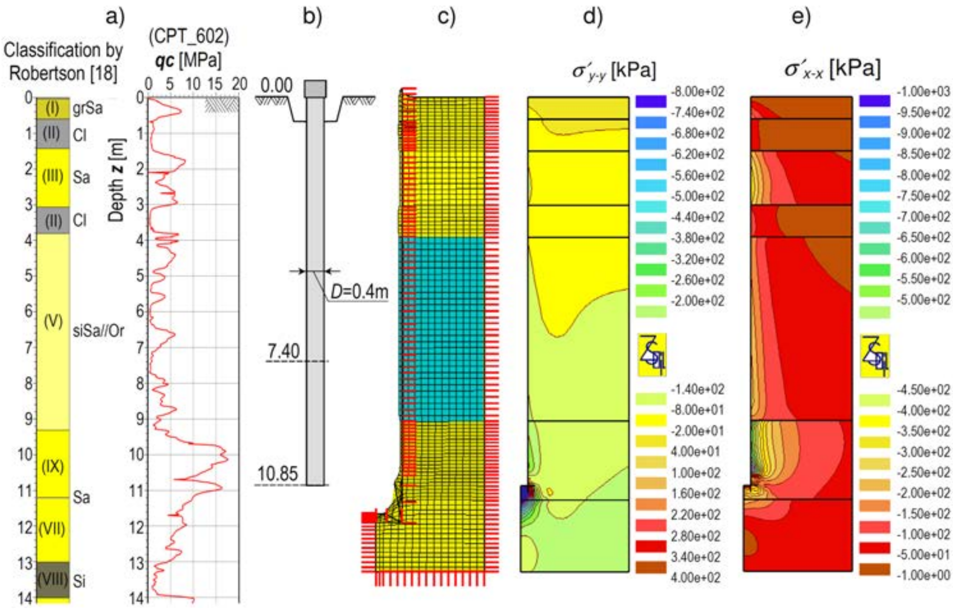

Fig. 6. Numerical test of pile 602 – geotechnical profile with q_c diagram from CPTU and the results of the soil expansion phase simulation – mesh deformation and effective stress maps

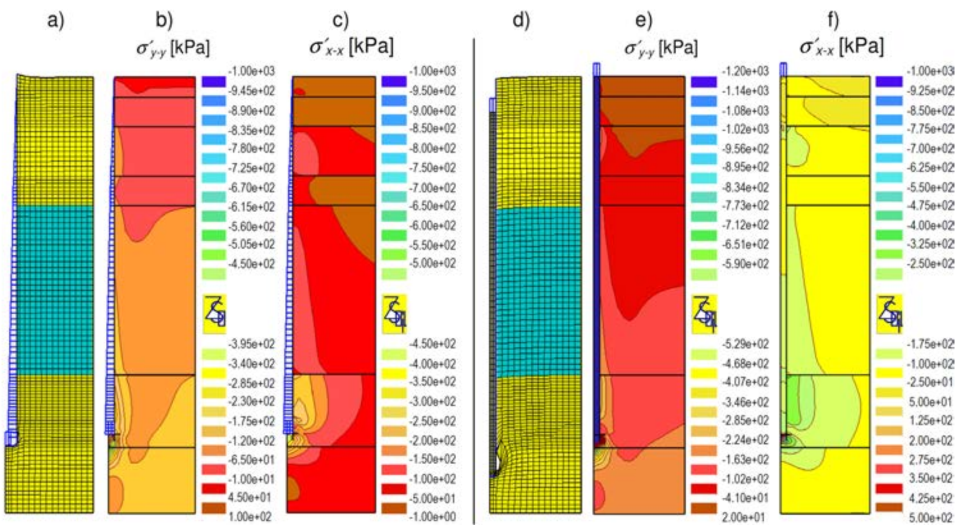

Fig. 7. Pile 602 – effective stress maps: a), b) concreting phase; c), d) load test phase

MOST WIEDZY Downloaded from mostwiedzy.pl

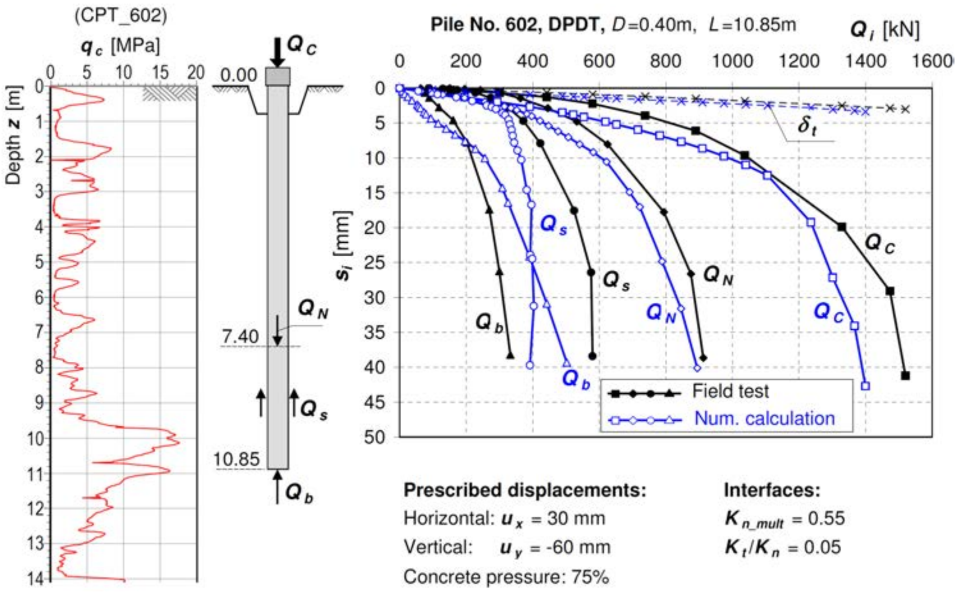

Fig. 8. Pile 602 – Q–s graphs from numerical calculations in comparison with real pile test

3.2. Pile 806 from test plot 2

The simulation example concerns pile 806, DPDT with diameter $D = 0.40$ m and length $L = 12.8$ m, [4]. The initial geotechnical parameters of the soil layers are listed in Table 2. The results of the numerical tests, in the form Q–s plots compared with the real pile test, are presented in Fig. 9.

Table 2. Initial parameters of soil layers adopted for numerical analyzes of pile 806, [4]

Soil layer	Soil type	Unit weight		Friction angle	Cohesion	Dilatancy angle	Stiffness modulus			Poisson's ratio	Reference pressure	Modulus exponent
		γ	γ_{sr}	φ'	c'	ψ	E_{50}^{ref}	E_{oed}	E_{ur}^{ref}	ν	p_{ref}	m
		[kN/m^3]		[°]	[kPa]	[°]	[MPa]			[–]	[kPa]	[–]
(I)	Sa+Si	19.0	20.0	35.0	0.0	3.0	25.0	30.0	50.0	0.2	100.0	0.5
(II)	FSa	18.5	19.5	33.0	0.0	2.0	20.0	25.0	40.0	0.2	100.0	0.3
(III)	clSi	19.5	20.0	30.0	25.0	0.0	6.0	6.0	12.0	0.2	100.0	0.8
(IV)	Cl/siSa	19.7	20.2	30.0	45.0	0.0	12.0	12.0	25.0	0.2	100.0	0.8
(V)	Sa/siSa	18.8	20.0	38.0	0.0	6.0	65.0	65.0	135.0	0.2	150.0	0.3
(VI)	siCl	20.2	20.2	30.0	50.0	0.0	25.0	25.0	50.0	0.2	200.0	0.9

MOST WIEDZY Downloaded from mostwiedzy.pl

www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

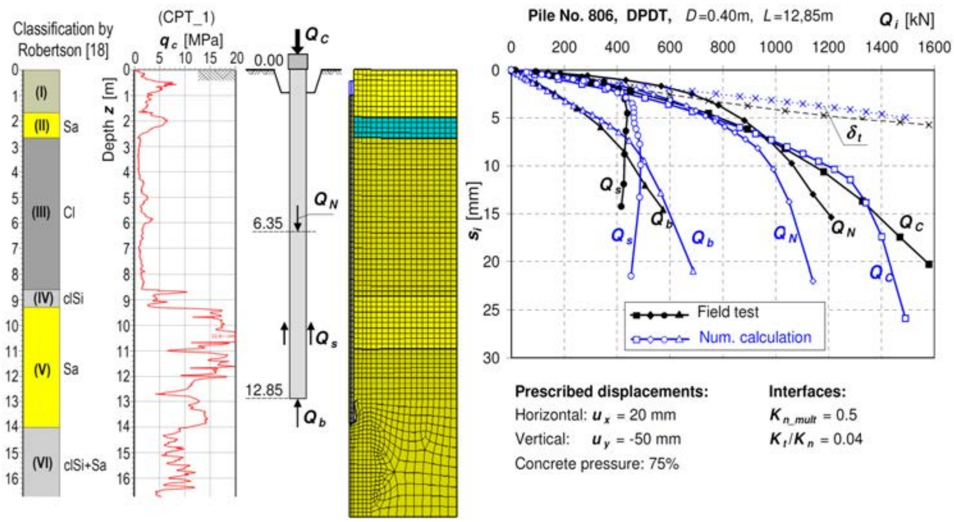

Fig. 9. Pile 806 – Q–s graphs from numerical calculations in comparison with real pile test

Analyzing the results presented in Fig. 8 and 9, the numerical representation of screw displacement piles interaction with subsoil can be assessed positively. Nevertheless, one can conclude that the initial stiffnesses of calculated Q–s curves seem to be underestimated in relation to test curves. The reasons of this underestimations can be the linear characteristic of E_{ur} soil modulus in HS constitutive model applied, the lack of taking into account the residual forces, commonly found in the displacement piles [20] and partially the lack of the small strain stiffness in HS model.

4. Conclusions

This article presents the tests and numerical simulations of two sample piles. In the research project, similar calibration tests were performed on about 10 piles selected from 6 specially prepared research plots. These tests confirmed that using the FEM ZSoil program it is possible to conduct a reliable numerical simulation and prediction of the interaction between a displacement pile and the subsoil. On the basis of these tests and analysis results, using the ZSoil program, the following conclusions and practical recommendations may be formulated with regard to simulations of screw displacement piles, taking into account pile installation phases:

1. The phase of auger soil expansion can be modeled using numerical displacements. Horizontal radial displacements of the pile hole walls are usually assumed to be u_x = 15–30 mm. In predictive modelling, for practical purposes, a value of u_x = 20 mm may therefore be proposed. Such a value can be considered safe (not causing overestimation).

MOST WIEDZY Downloaded from mostwiedzy.pl

2. During the same phase of soil expansion, numerical vertical pile hole bottom displacements of $u_y = 30{-}60$ mm had to be set. For practical predictive numerical calculations, $u_y = 40{-}50$ mm is therefore proposed. Such a range will be safe (not causing overestimation).
3. The same modeling parameters of the pile concreting phase were used in all the analyzed cases, with p_x and p_y equal to 75% of the concrete mix hydrostatic pressure. This has yielded good results. The same method and values are therefore proposed to be used in predictive modeling.
4. An important element of the above simulations was the proper adoption of contact (interface) parameters in the form of the stiffness coefficients $K_{n\_\mathrm{mult}} = 0.5$ and $K_t/K_n = 0.03{-}0.05$, selected by trial and error. Similar values are proposed for practical, engineering numerical calculations. The analyses showed that numerical calculations are very sensitive to these parameters. The proper selection of parameter values requires further research and remains an open topic for discussion.

Acknowledgements

The article was based on research and analyses carried out in "DPDT-Auger" project no. POIR.04.01.04-00-0124/18 "Development of a method and tools for the installation of screw displacement columns/piles in various ground conditions in Poland, together with the preparation of a methodology for the design and acceptance of works" carried out by the Budokop Geotechnika (leader) and the Gdańsk University of Technology consortium. The project was financially supported by the Polish National Centre for Research and Development.

References

[1] PN-EN:1997-1:2008 – Eurocode 7: Geotechnical design – Part 1: General rules. Brussels; Warsaw, 2008.

[2] A. Krasiński, *Pale przemieszczeniowe wkręcane. Współpraca z niespoistym podłożem gruntowym*. Politechnika Gdańska, Monografie, vol. 134. Gdańsk, 2013.

[3] A. Krasiński, "Świder do wykonywania pali przemieszczeniowych wkręcanych (Auger for making screw displacement piles)", Poland. Patent PL 235442 B1, Aug. 10, 2020.

[4] A. Krasiński, P. Więcławski, W. Tisler, T. Kusio, and M. Wiszniewski, *Raport końcowy z projekt badawczego "DPDT-Auger", nr POIR.04.01.04-00-0124/18: "Opracowanie metody i narzędzi do wykonywania kolumn/pali przemieszczeniowych wkręcanych w różnorodnych warunkach gruntowych na obszarze Polski wraz z przygotowaniem metodyki do projektowania i odbioru robót*". Gdańsk, 2022.

[5] S. Commend, S. Kivell, R.F. Obrzud, K. Podleś, A. Truty, and Th. Zimmermann, *Computational geomechanics. Getting started with ZSOIL.PC*. Lausanne, Switzerland, 2015.

[6] Th. Zimmermann, A. Truty, and K. Podleś, *Numerics in geotechnics and structures*. Switzerland: Rossolis Editions & Zace Services Ltd., 2015.

[7] A. Truty, Th. Zimmermann, K. Podles, and R.F. Obrzud, *ZSoil manual*. Lausanne, Switzerland: Elmepress and Zace Services Limited, 2016.

[8] A. Truty and R. Obrzud, *The hardening soil model – a practical guidebook. Z_Soil.PC 100701 report revised 2.01.2020*. Lausanne, Switzerland: GeoDev Sarl, 2020.

[9] A. Krasiński and M. Wiszniewski, "Static load test on instrumented pile – field data and numerical simulations", *Studia Geotechnica et Mechanica*, vol. 39, no. 3, pp. 17–25, 2017, doi: 10.1515/sgem-2017-0026.

Downloaded from mostwiedzy.pl MOST WIEDZY

[10] K.-P. Mahutka, F. König, and J. Grabe, "Numerical modelling of pile jacking, driving and vibro driving", in *Proceedings of International Conference on Numerical Simulation of Construction Processes in Geotechnical Engineering for Urban Environment*, T. Triantafyllidis, Ed. Rotterdam: Balkema, 2006, pp. 235–246.

[11] S. Henke and J. Grabe, "Numerical modelling of pile installation", *in Proc. of 17th International Conference on Soil Mechanics and Foundation Engineering.* Alexandria, Egypt, 2009, pp. 1321–1324.

[12] P. Basu and M. Prezzi, *Design and Applications of Drilled Displacement (Screw) Piles. Final Raport FHWA/IN/JTRP-2009/28*. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, 2009.

[13] A. Krasiński, "Numerical simulation of screw displacement pile interaction with non-cohesive soil", *Archives of Civil and Mechanical Engineering*, vol. 14, no. 1, pp. 122–133, 2014, doi: 10.1016/j.acme.2013.05.010.

[14] A. Krasiński and T. Kusio, "Load-settlement characteristics of piles working in a group", presented at 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, 2017.

[15] J. Konkol, "Numerical analysis of pile installation effects in cohesive soils", PhD thesis, Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, 2018.

[16] M. Cudny, *Some aspects of the constitutive modelling of natural fine grained soils*. Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Wydawnictwo IMOGEOR, 2013.

[17] T. Schanz and P.A. Vermeer, "Angles of friction and dilatancy of sand", *Géotechnique*, vol. 46, no. 1, pp. 145–151, 1996, doi: 10.1680/geot.1996.46.1.145.

[18] P.K. Robertson, "Soil classification using the cone penetration test", *Canadian Geotechnical Journal*, vol. 27, no. 1, pp. 151–158, 1990, doi: 10.1139/t90-014.

[19] R. Salgado and M.F. Randolph, "Analysis of cavity expansion in sand", *International Journal of Geomechanics*, vol. 1, no. 2, pp. 175-192, 2001, doi: 10.1061/(ASCE)1532-3641(2001)1:2(175).

[20] A. Krasiński and M. Wiszniewski, "Identification of residual force in static load tests on instrumented screw displacement piles", *Studia Geotechnica et Mechanica*, vol. 43, no. 4, pp. 438–451, 2021, doi: 10.2478/sgem-2021-0025.

Modelowanie MES współpracy pali przemieszczeniowych wkręcanych z podłożem gruntowym

Słowa kluczowe: metoda elementów skończonych, ZSoil, pale przemieszczeniowe wkręcane, charakterystyka osiadania pala

Streszczenie:

Prognoza osiadania pali fundamentowych pod wpływem obciążeń zewnętrznych jest kluczowym zagadnieniem w projektowaniu posadowień głębokich. Dysponując charakterystyką „*Q*–*s*" (obciążenie–osiadanie) można z dobrą dokładnością określić w jaki sposób będzie zachowywała się konstrukcja w trakcie budowy i użytkowania. Najlepszą metodą weryfikacji współpracy pali z podłożem jest próbne obciążenie statyczne, szczególnie cenne w przypadku pali oprzyrządowanych, gdy poza globalną charakterystyką dysponujemy dodatkowo pomiarami oporów gruntu pod podstawą i tarcia na pobocznicy. Ze względu na ograniczenia techniczne i ekonomiczne nie zawsze istnieje możliwość wykonania satysfakcjonującej liczby testów w terenie z zaawansowanym oprzyrządowaniem pomiarowym. Problem częściowo rozwiązuje możliwość symulacji numerycznej. W artykule przedstawiono propozycję procedury modelowania współpracy pali przemieszczeniowych, formowanych za pomocą świdrów rozpierających DPDT, z ośrodkiem gruntowym w programie ZSoil 2018. Rozpatrywany problem potraktowano jako zagadnienie początkowo-brzegowe, dotyczące pala pojedynczego, wymodelowane w układzie osiowo-symetrycznym. Pal wyrażono za pomocą elementów

MOST WIEDZY Downloaded from mostwiedzy.pl

objętościowych. Przedstawiona procedura uwzględnia czynniki technologiczne charakterystyczne dla tego typu pali, takie jak proces rozpierania gruntu przez wkręcanie świdra czy ciśnienie mieszanki betonowej. Procesy te wymodelowano sposobami zastępczymi. Wpływają one istotnie na stan naprężenia w gruncie, czyli kluczowy parametr, od którego zależy nośność pala. Wzdłuż linii styku pala z gruntem (wzdłuż pobocznicy i pod podstawą) zastosowano elementy kontaktowe („interface"). Elementy te są opisywane typowymi parametrami gruntowymi, ale oprócz tego parametrami K_{n_mult} oraz K_t/K_n. Wartości tych oraz innych parametrów określano na podstawie prób kalibracyjnych. W modelu geometrycznym, uwarstwienie podłoża gruntowego dostosowywano do profilu geotechnicznego wyznaczonego z sondowania statycznego CPTU. Ze względu na znaczną złożoność zagadnienia (fazy z obciążeniami i odciążeniami), w analizach wykorzystano model konstytutywny gruntu „Hardening Soil". Procedura modelowania została skalibrowana na podstawie wyników próbnych obciążeń statycznych kilku pali oprzyrządowanych pomiarowo, które wykonano w ramach projektu badawczego „DPDT-Auger" nr POIR.04.01.04-00-0124/18 dofinansowanego z NCBiR i środków UE. W wyniku kalibracji wyprowadzono uogólnione zalecenia dotyczące całego procesu modelowania pala pojedynczego w układzie osiowosymetrycznym programu ZSoil, jak również dotyczące wartości parametrów poszczególnych etapów tego modelowania. Pozwolą one na miarodajne i wiarygodne prognozowanie MES charakterystyk „Q–s" pali przemieszczeniowych wkręcanych, przydatnych w praktyce projektowej.

Received: 2023-03-27, Revised: 2023-04-06

MOST WIEDZY Downloaded from mostwiedzy.pl

View publication stats