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Back Analysis of Full-Scale Field Test Results on Piles Installed in Soft Soils Using PLAXIS 2D Software

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ABSTRACT: A back analysis study of soil-pile interaction in soft soils has been performed using finite element method with advanced constitutive soil models. The models were determined based on laboratory test results and calibrated using full-scale field test data from a construction site located in Esbjerg, Denmark. Two instrumented, 12 m embedment, 406 mm diameter tubular steel piles and two instrumented, 12 m embedment, 350 mm square precast concrete piles were installed through a 3.5 m thick layer of reclaimed sand underlain by a 3.6 m thick layer of soft soil followed by a dense sand layer. The soft soil layer consists of postglacial gyttja and peat. Construction activities and sequence around the test piles had a significant effect on the test piles response and made the interpretation of the results difficult. Therefore, a simulation was carried out using PLAXIS 2D to investigate and understand the observed soil-pile interaction.

KEYWORDS: Driven piles, pile instrumentation, distributed fiber optic sensors, negative skin friction, lateral thrust, field monitoring.

1 INTRODUCTION

Back-analysis is widely used in geotechnical engineering to verify design assumptions, investigate failures, and improve understanding of soil–structure interaction mechanisms (Caicedo et al., 2019; Kort & van Tol, 2002). For pile foundations affected by construction activities, back-analysis is particularly valuable because field measurements are often influenced by temporal and spatial variability that complicates interpretation.

Recent advances in distributed fiber optic sensing (DFOS) have enabled high-resolution strain measurements along piles, offering new insight into the development of shaft resistance and soil–pile interaction (Kania et al., 2020a). However, DFOS interpretation becomes challenging when piles are subjected to combined axial and lateral loading or when construction activities modify the surrounding stress field. These conditions can distort the measured strain distribution and hinder reliable assessment of internal and external forces.

Finite Element Method (FEM) modelling is widely used to simulate soil–pile interaction yet modelling piles in organic soft soils such as gyttja and peat remains difficult due to their high compressibility, high organic content, and pronounced time-dependent behavior. Previous studies (e.g., Zhao et al., 2022) indicate that predicting internal forces, drag forces, pile deformation, and ground settlement require careful calibration of constitutive models and precise representation of construction sequencing. Despite this, few studies have integrated full-scale DFOS monitoring with advanced soil models and detailed back-analysis, and even fewer have examined the impacts of construction-induced disturbances on measured pile response.

The Esbjerg Strand project (Figure 1) provides an opportunity to address these gaps. Four instrumented piles were installed through reclaimed sand into organic soft soils, but extensive construction activities disrupted the monitoring program and introduced uncertainties into the field data.

This study performs a detailed back-analysis using PLAXIS 2D, calibrated against DFOS and ground monitoring results, to provide more reliable internal-force distribution and lateral deformation profiles, and to improve understanding of soil–pile interaction under complex construction conditions.

Figure 1. The Esbjerg Strand project (source: www.esbjerg.dk).

2 MATERIALS AND METHODS

2.1 *Soil and ground water conditions*

The boreholes indicated a soil profile consisting of a 2.0 m thick layer of fine to coarse sand, followed by a 3.6 m thick layer of soft soil composed of postglacial marine, organic gyttja and peat underlain by a dense sand layer.

The average unit density, ρ, of gyttja and peat was 1,490 kg/m³ and 1,140 kg/m³, respectively. The water content, w_n, of the entire soft soil layer ranged from 77 % to 273 %. The plastic limit, w_p, ranged from 63 % to 383 % and the liquid limit, w_l, ranged from 145 % to 499 %. The undrained shear strength, c_u, of the soft soil layer, determined based on the CPTU soundings applying a cone factor, N_k, of 15, was 16 kPa.

Four oedometer tests performed on specimens (one gyttja and 3 peat) sampled at between 4.1 and 5.33 m depth showed a compression index, C_c, of 0.66 and 2.61, and swelling index, C_s, of 0.11 and 0.39 for gyttja and peat, respectively. Initial void ratio, e_{init}, was 1.8 for gyttja and 4.84 for peat. The over consolidation ratio, OCR, for all four specimens was lower than 2. The coefficient of permeability, k, was $2 \cdot 10^{-9}$ m/s for gyttja and $1 \cdot 10^{-9}$ m/s for peat.

The organic content in the soft soil layer ranged from 12.9 to 91.4 % with an average of 56 %.

2.2 *Test setup, instrumentation and schedule*

The test setup consisted of four instrumented test piles and a ground monitoring system as presented in Figure 2.

Two instrumented, 12-meter embedment, 406-millimeter diameter tubular steel piles and two instrumented, 12-meter embedment, 350-millimeter square precast concrete piles were installed at the site. One pile of each type was coated with 1 mm thick layer of 80/100 penetration bitumen (CTP2 and STP2). All test piles were instrumented with a pair of oppositely mounted strain distributed fiber optic sensors (DFOS). Additionally, the steel test piles were equipped with one line of several vibrating wire strain (VWS) gauges.

The ground monitoring system was comprised of one string of vibrating wire piezometers, one string of magnetic extensometers (6 leaf spider magnets), two settlement plates and one standpipe with the intake zone at 12.5 m depth. The details of the test pile instrumentation, setup, schedule and soil conditions are presented in Kania et al. (2020b).

The planned test schedule consisted of two phases during which the effect of pile installation (Phase 1) and development of negative skin friction after placing a fill (Phase 2) was investigated. Unfortunately, the intended schedule was disturbed due to construction activities such as one-sided loading, excavation near the test piles, installation of anchor plates, heavy machinery and trucks passing next to the test piles.

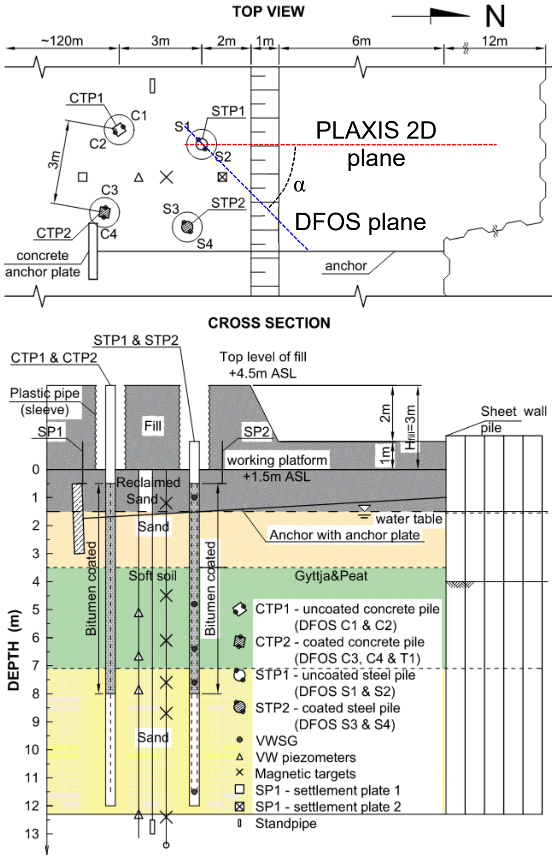

Figure 2. Test setup and soil profile (Kania 2020b).

2.3 *Strain data analysis and interpretation*

The measured strain records from DFOS were thermally corrected using the temperature records from VWS gauges (mounted on the steel test pile) to obtain the mechanically induced strains. Based on the mechanically induced strains, the internal forces (axial force, bending moment and shear force) and lateral deflection of the test piles were determined. The details regarding temperature compensation, strain data interpretation as well as filtering and smoothening of the DFOS data are provided in Kania et al. (2020a).

2.4 *Numerical model*

The numerical analysis was carried out using PLAXIS 2D software. The plain strain model is shown in Figure 3. The dimensions of the model were 26 m x 60 m (height x width). All boundaries except the bottom are draining to allow water flow during consolidation analysis. The soil stratigraphy comprises five distinct layers: reclaimed sand, marine sand, postglacial gyttja, and postglacial peat as soft soils, underlain by a dense sand layer. The model incorporated two test piles of 12 m length and an anchored sheet pile wall. The piles were modelled as embedded beams (the interface factor included in the formulation) with 3.0 m spacing. The CTP pile was modeled as a solid square section with Young's modulus of 32.8 GPa, whereas the STP pile was modeled as a circular tube with Young's modulus of 210 GPa. The sheet pile wall was modelled as a plate element with EA = 5.13E^6 kN/m and EI = 2.10E^5 kNm^2/m, and the anchor was modelled as a fixed-end-anchor.

A 15-node triangular element and a medium mesh density with an average mesh quality of 0.9 (number of soil elements: 2071) were employed in numerical analysis. This mesh resolution was deemed sufficiently fine to ensure accurate results and avoid numerical errors.

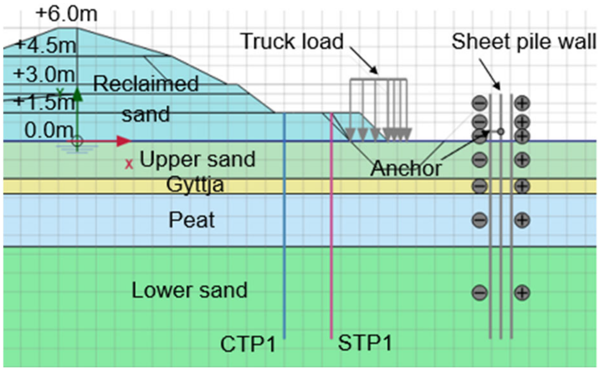

Figure 3. PLAXIS 2D model at one of the interim calculation phases.

The soil stratigraphy and parameters are presented in Table 1. The reclaimed sand, upper sand and lower sand layers were modelled using a drained Mohr-Coulomb (MC) soil model. The gyttja and peat layers were modelled utilizing a Soft Soil (SS) model. Mohr-Coulomb material model was employed for sand layers to simplify the calibration process and due to lack of field and laboratory data. The model was described using the compression and swelling indices obtained from the laboratory tests. The interface strength reduction factor, R_{inter}, of 0.45 was adopted from Kania et al. (2024).

To simulate the construction activities several calculation phases were introduced in the model. Beside the initial phase with the ground surface located at 0.0 m DVR90, the construction of working platform (+1.5 m DVR90) and installation of the test piles were modelled. Afterwards, backfilling up to +6.0 m DVR90 was simulated causing one-sided loading and imposing lateral thrust on the test piles. Next, a sheet pile wall was introduced confining the area around the test piles. Then the first consolidation phase was modelled lasting 126 days (after pile installation). Thereafter, preparations for backfilling were initiated. Firstly, the area around the test piles was excavated to install the deadman anchors and afterwards backfilled to allow traffic for heavy equipment and trucks. The trucks delivered reclaimed sand to backfill the entire area to the design elevation of +4.5 m

DVR90. In the meantime, the soil in front of the sheet pile wall was excavated down to -2.0 m DVR90 enclosing the reclaimed area and the second consolidation phase started and was observed until 722 days after installation of the test piles.

Table 1. Model soil stratigraphy and parameters.

Parameter	Fill[(1)]	Upper sand	Gyttja	Peat	Lower sand
Material model	MC	MC	SS	SS	MC
y_{max} [m]	+1.5	0.0	-2.0	-2.8	-5.6
y_{min} [m]	0.0	-2.0	-2.8	-5.6	-20
γ_{unsat} [kN/m³]	17.0	18.0	14.9	11.4	18.0
γ_{sat} [kN/m³]	18.0	20.0	14.9	11.4	20.0
e_{init} [-]	0.90	0.60	1.80	4.84	0.40
E'_{ref} [MN/m²]	5	10	-	-	100
ν [-]	0.2	0.25	0.15	0.15	0.35
c'_{ref} [kN/m²]	1	1	5	3	0.1
φ' [°]	31	33	25	22	35
k_x [m/day]	8.64	8.64	$1.7E^{-4}$	$8.64E^{-5}$	8.64
k_y [m/day]	8.64	8.64	$1.7E^{-4}$	$8.64E^{-5}$	8.64
C_c [-]	-	-	0.61	2.66	-
C_s [-]	-	-	0.11	0.39	-
OCR	-	-	2	2	-
R_{inter}	0.45	0.45	0.45	0.45	0.45

(1) Fill consists of reclaimed sand

3 RESULTS AND DISCUSSION

To calibrate the finite element model the measured and simulated ground settlement, internal forces (bending moment and shear force) and lateral deformation of the uncoated steel test pile (STP1) were compared. It is important to note that the plane created by two oppositely mounted DFOS sensors is different than the assumed plane in PLAXIS 2D model as indicated in Figure 2. Therefore, to align the simulated bending moment (and shear force) distributions with the measured ones, the simulated records were multiplied by cos(α), with α = 45° being the assumed average angle between the two planes. Unfortunately, the exact angle between the planes is not known.

3.1 *Soil settlements*

Figure 4 presents the measured and simulated soil settlement profile 126 days and 722 days after installation of the test piles. As shown in the figure, the simulated settlement profiles match the measurements well especially within the peat layer. A possible explanation for the discrepancy in soil settlement at the top might be that the consolidation indices obtained from the oedometer test (only one test) were not representative for the entire gyttja layer.

3.2 *Internal forces along the uncoated steel test pile*

The measured and simulated distributions of bending moment and shear force are presented in Figure 5. The measured internal forces were determined based on the mechanically induced DFOS strain records assuming the Young's modulus of steel equal to 210 GPa. As mentioned, the simulated distributions were multiplied by the assumed angle, α, between DFOS and PLAXIS 2D planes. By changing the angle, α, the magnitude of bending moment (and shear force) will change, however, the overall distribution of internal forces will remain similar. As can be seen in Figure 5 a), the measured and simulated bending moment at 126 days after pile installation is in general agreement, showing both positive and negative, extreme values.

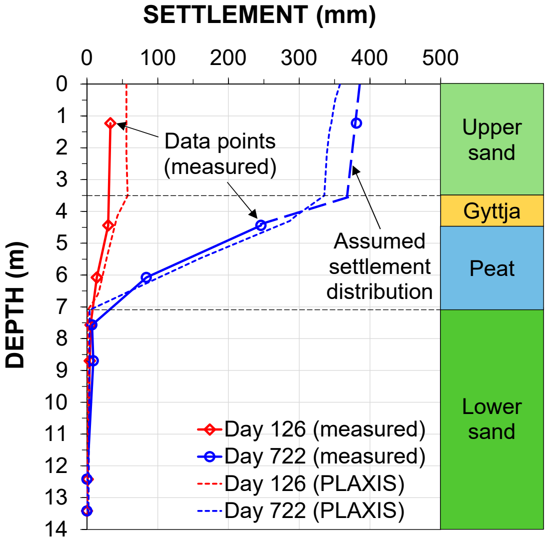

Figure 4. Measured and simulated settlement 126 days (just before final backfilling around the test piles) and 722 days after pile installation. Measured data based on Kania et al. (2020b).

By changing the angle, α, the magnitude of bending moment (and shear force) will change, however, the overall distribution of internal forces will remain similar. As can be seen in Figure 5 a), the measured and simulated bending moment at 126 days after pile installation is in general agreement, showing both, positive and negative, extreme values. However, 722 days after pile installation the measured bending moment shows solely positive values indicating bending of the pile only in one direction. A possible explanation for this might be that some construction activities affecting the upper part of the test pile were not captured or wrongly simulated in the PLAXIS 2D model.

Similarly, as presented in Figure 5 b), the measured and simulated shear force distribution 126 days after pile installation is in general agreement. Both indicate shear planes near the boundaries between sand and soft soil layer (at 3 and 7-8 m depth).

Tensile strains occurred at the location of shear planes making the interpretation of the DFOS determined axial force very difficult and resulted in unrealistic distributions as shown in Figure 6 (positive values denote compression). This result may be explained by the fact that the test pile was not only loaded axially but was also subjected to lateral forces. The simulated axial force distribution with the maximum drag force of about 90 kN at 722 days after pile installation is considered more reliable.

3.3 *Lateral displacement of the uncoated steel test pile*

The lateral displacement of the uncoated steel test pile at 126 and 722 days after pile installation is shown in Figure 7. Both measured and simulated, distributions are in good agreement within the soft soil layer and below. However, in the upper part the results differ. The influence of the assumed angle between PLAXIS 2D and two opposite mounted strain DFOS cables cannot be ruled out. However, this factor will only change the magnitude of lateral displacement and not the overall distribution. Another possible explanation for this, as previously mentioned, is that some of many construction activities taking place around the test piles may unintentionally not be included in the model causing the deflection of the pile especially in the upper part.

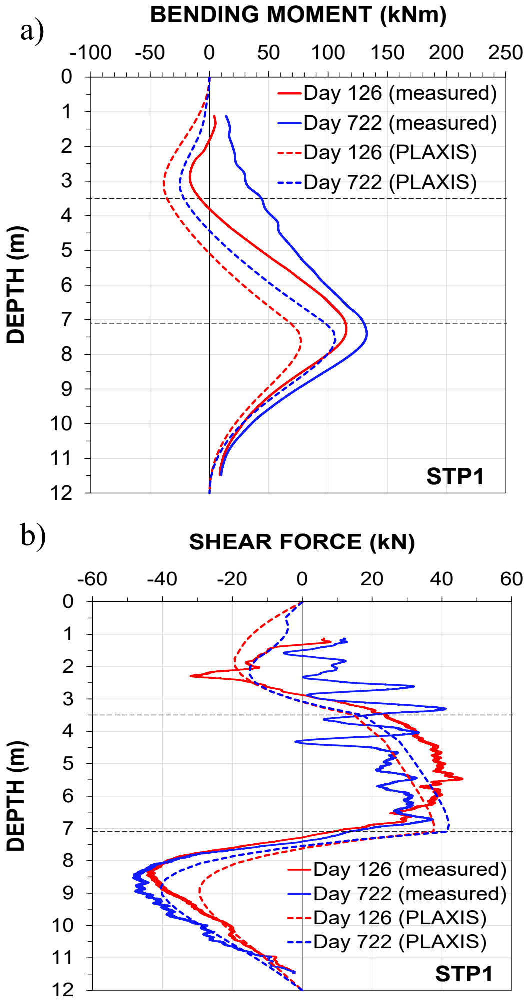

Figure 5. Measured and simulated a) bending moment and b) shear force distribution along the uncoated steel test pile at 126 and 722 days after pile installation. Measured data based on Kania et al. (2020b).

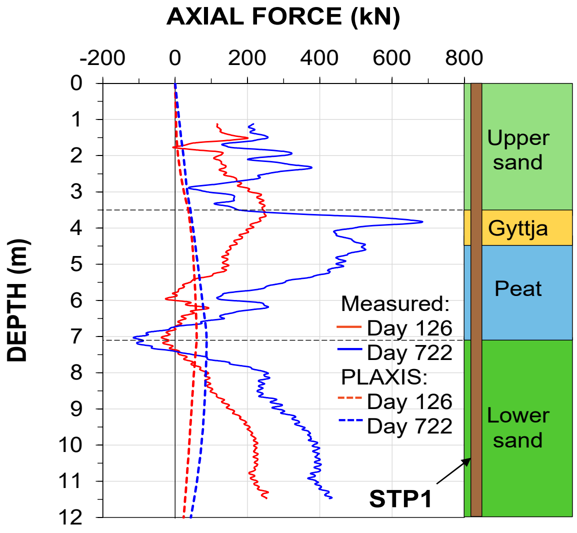

Figure 6. Measured and simulated axial force distribution along the uncoated steel test pile at 126 and 722 days after pile installation. Measured data based on Kania et al. (2020b).

4 CONCLUSIONS

The purpose of the current study was to investigate the soil-pile interaction in soft soils by determining a suitable PLAXIS 2D model and comparing measured and simulated internal forces and lateral deflection of the uncoated steel test pile.

This study has shown that:

- It is possible to establish a suitable soil model in PLAXIS 2D based on soil laboratory tests. However, with a small number of laboratory tests, caution must be applied in determining soil model parameters, as individual laboratory test results might not be transferable to a global soil model.
- Back analysis of internal forces and lateral displacement along the uncoated steel test pile conducted in PLAXIS 2D helped to validate the model and obtain more reliable drag-force distribution.
- All construction activities should be noted and modelled in order to correctly simulate the soil-pile interaction.

The current study has only investigated the soil-pile interaction along the uncoated steel driven pile. Further work needs to be done to establish the behavior of bitumen coated piles, different pile material, e.g. concrete, or pile type, e.g. bored piles.

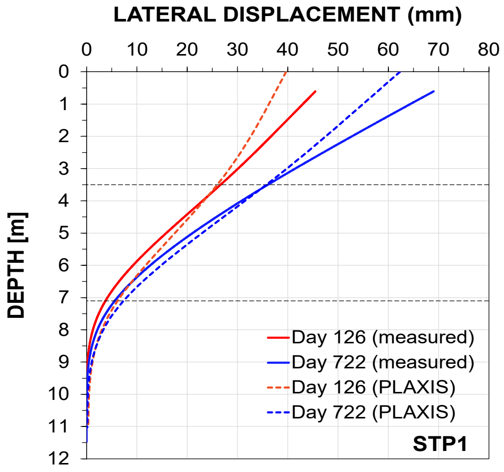

Figure 7. Measured and simulated lateral displacement of the uncoated steel test pile at 126 and 722 days after pile installation. Measured data based on Kania et al. (2020b).

5 ACKNOWLEDGEMENTS

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