PILED FOUNDATION FOR THE CONTAINER TERMINAL AT YDRE NORDHAVN

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KEYWORDS

Driven piles, Concrete slab, Limestone, Dynamic tests, Soil set-up, Global Mapper

ABSTRACT

As part of the development of the Nordhavn area in Copenhagen a new container terminal is under construction (2024). The new container terminal is located on a reclaimed land with a stock yard area of around 133,000 m2 paved with a concrete slab supported by more than 4000 concrete driven piles. The pile sizes varied between 250 mm x 250 mm and 350 mm x 350 mm. Generally, the soil conditions at the site consisted of 15-23 m of reclaimed material (clay or sand fill) on top of gyttja underlain by limestone. Part of the gyttja layer was placed as a membrane in order to separate polluted reclamation fill from the naturally deposited gyttja underneath. The limestone elevation was found between -15 m DVR90 and -23 m DVR90. The borehole records indicate that the degree of induration varies from H1 to H5.

The aim of this paper is to describe the piled foundation design approach, where the limestone surface and required pile toe elevation for all production piles were established based on borehole and test pile data, respectively. The paper provides detailed site conditions, determination of soil set-up factor and the design approach. Finally, a statistical approach to treating, compiling, and evaluating the data for the installation of the 4000+ production piles is presented.

1. INTRODUCTION

Driven prefabricated reinforced concrete piles are the default choice for a piled foundation in Denmark unless prevented by environmental issues or capacity restrictions. To achieve a high required pile resistance, piles frequently penetrate very stiff or dense soils or rocks. This places high demand on the structural capacity of the piles.

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For the new container terminal project, which is a part of the development of the Nordhavn area in Copenhagen, driven prefabricated reinforced concrete piles were chosen as foundation below a large concrete slab that supports the stock yard area of around 133,000 m². To limit the settlements of the slab the piles were required to be installed into limestone to rely on very high toe resistance.

To optimize the design of the involved 4000+ piles a major testing campaign was initiated. The goal was to establish robust driving criteria for the piles to avoid damage to the piles and at the same time ensuring that the target capacity could be reached. To achieve these goals test piles were driven and re-driven with complete driving records followed by PDA/CAPWAP testing. The latter allowed for estimation of the set-up after pile driving to be established.

The paper describes the design approach used for the project, the on-site handling of the pile driving and provides insight into the way the statistical data, based on the test piles and the installation of production piles allowed for overall management of the pile driving process.

Figure 1 Site location [4].

2. MATERIALS AND METHODS

Construction site

The construction site is an area in the harbour of Copenhagen reclaimed between 2012 and 2022. As illustrated in Figure 2, part of the reclaimed area was subjected to preloading by placing a temporary fill (marked with red lines on the figure). Another part of the reclaimed area (marked with light blue lines on Figure 2), partly overlapping the preloaded area, was initially covered with a layer of gyttja, as a membrane, in order to separate more or less polluted reclamation fill from the natural soil deposit underneath. The reasons for the shape of the preloading area and gyttja membrane are not known. However, it seems possible that the preloading area was meant to cover the area with the thickest gyttja layer as shown in Figure 3.

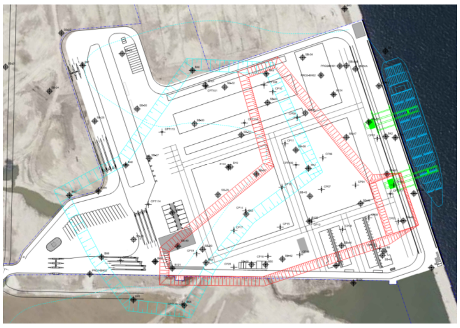

Figure 2 Construction site with the assumed location of the pre-consolidation (marked with red) and the approximate area of gyttja-membrane (marked with light blue) [3].

Figure 3 Variation of gyttja thickness at the construction site [3].

Soil conditions

Ground investigation campaigns between 2006 and 2022 indicated a soil profile consisting of a 15-23 m thick layer of reclaimed material (soft to stiff clay or loose to compact sand fill) underlain by up to 7 m thick layer of gyttja on top of limestone. Some boreholes indicate a late glacial or glacial gravel layer (up to 7 m thick) between gyttja and limestone. The undrained shear strength of gyttja derived based on the field vane test results and correlation factor of 0.8 was found between 30 and 110 kPa. The unconfined compressive strength of limestone is presented in Figure 4. The lower bound 95% confidence limit and mean value are 12.7 MPa and 19.9 MPa, respectively.

The top of the limestone across the construction site presented as an elevation heat map is shown in Figure 5. The heat map was created in a commercial software called Global Mapper [1] using the coordinate data from the available boreholes. As can be seen from the figure the top of the limestone is located between -14.6 m DVR 90 and -23.5 m DVR90.

Pile test programme

The test programme consisted of two phases of dynamic tests. In the first and second phase 30 and 97 test piles were installed and tested in two rounds, respectively. The first round of the dynamic tests was performed between 1 and 4 days after pile installation. The second round of the dynamic tests was conducted at least 7 days after the first round. Different pile sizes (250 mm, 300 mm and 400 mm) and lengths (21 – 31 m) were used in the test campaign.

The main goal of the testing campaign was to find the achievable pile resistance and potential soil set-up factor allowing driving and termination criteria for all the production piles to be established. The pile resistance was determined with CAPWAP analysis. The soil setup, i.e. gain in pile resistance with

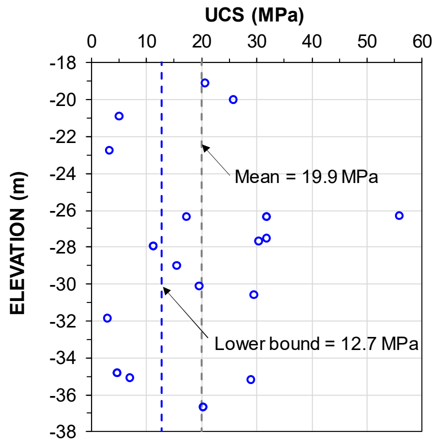

Figure 4 Unconfined compression strength of limestone.

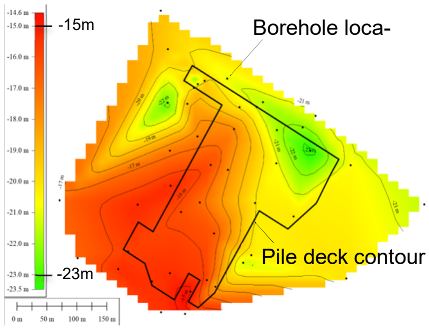

Figure 5 Top of limestone elevation with the pile deck contour and location of the boreholes.

time, was established based on two rounds of CAPWAP measurements and extrapolated to values 28 days after pile installation. Afterwards, the extrapolated pile resistance was divided by the initial end-of-driving resistance in order to obtain the soil set-up factor. The end-of-driving resistance was determined based on Danish Pile Driving Equation (DPDE). The driving and termination criteria (including the potential soil set-up factor) were determined to avoid hard driving and damage to the piles.

Data collection

Managing data from driving journals for over 4000 piles across various spreadsheets is cumbersome and resource intensive. To streamline this process, a single Excel tool has been created. This tool allows for easy importation of individual or multiple driving journals in Excel format with the click of a button. Utilizing Visual Basic for Application (VBA), the tool imports data and calculates pile capacity, ensuring convenient access to specific pile information. Additionally, it can import CAPWAP test results from PDFs, achieved through a combination of VBA and Power Query to convert the PDF into tabular format. The tool offers various features, including a plan for tracking pile status and the ability to create depth-based capacity charts.

Determination of the expected length of production piles

The main requirement for the installation of all the production piles was to embed them into limestone. The top of limestone was determined for all the production piles based on the map from Figure 5. The design axial compression pile load in the ultimate limit state was 1400 kN. The elevation, at which a test pile reaches an equivalent pile resistance measured at the end-of-driving (including the potential soil set-up factor, correlation, and partial factors), was determined for every test pile as presented in Figure 6. Afterwards, similar to the creation of the top of limestone elevation heat map, another heat map was established showing elevations at which piles were assumed to reach the required end-of-driving resistance (or ULS load).

Assessment of production pile installation

Driving records of all the production piles (4000+ piles) were stored in digitized driving journals. All the journals were imported daily to the project's dedicated excel spreadsheet to assess the installation of the production piles. The initial assessment was done automatically by the spreadsheet following the prescribed criteria:

- "Green" when a pile reached the required pile resistance and the expected top of the limestone.
- "Yellow" when a pile reached the required pile resistance, but its pile toe was located up to 0.5 m above the expected top of the limestone.
- "Red" when a pile did not reach the required pile resistance, its pile toe was located more than 0.5 m above the expected top of the limestone, or its pile head was located below the required elevation (i.e. the pile was installed too deep)

Every pile was checked by an engineer after the initial assessment.

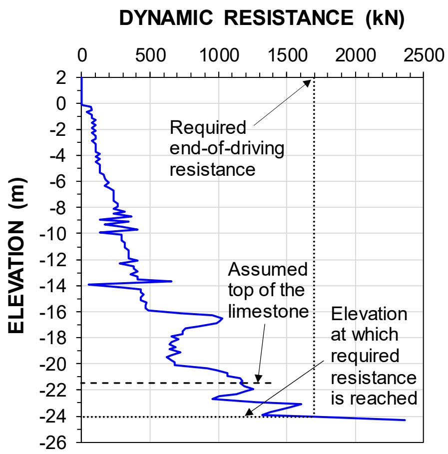

Figure 6 Determination of the expected pile toe elevation for a single test pile

3. RESULTS

Soil setup

Figure 7 presents an example of CAPWAP resistance extrapolation analysed for one of the test piles. The first round of dynamic test with CAPWAP analysis conducted 4 days after pile installation indicated a total pile resistance of 3190 kN. The second round of test revealed a pile resistance of 3680 kN. The extrapolated CAPWAP resistance on 28th day after pile installation was

4000 kN. Such analysis was performed for every test pile and created a basis for determination of the soil set-up factor.

The obtained soil set-up factor is shown in Figure 8. The vertical axis shows a pile resistance extrapolated on 28th day after pile installation based on two rounds of CAPWAP measurements. The horizontal axis represents a pile resistance determined by DPDE at the end-of-driving (EOD). It was decided to compare the CAPWAP determined resistance with DPDE at EOD resistance because it was planned to verify all the production piles using that method

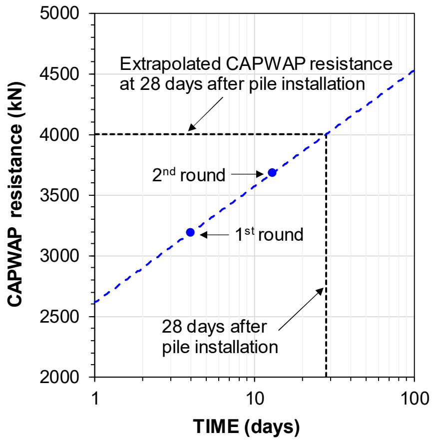

Figure 7 Example of CAPWAP resistance extrapolation.

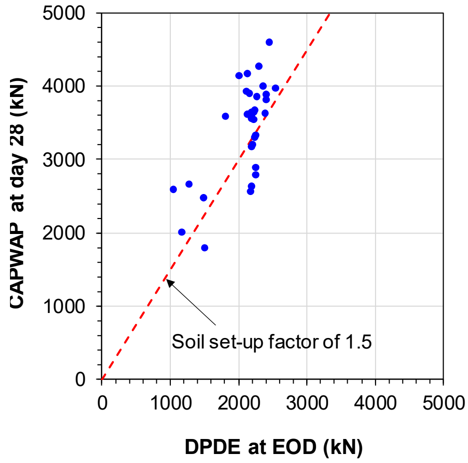

Figure 8 Soil set-up factor.

(i.e. DPDE at EOD). The average soil set-up factor was 1.63. However, it was decided to use a soil set-up factor of 1.5 as indicated in the figure by a red, dashed line. It is important to mention that in average the CAPWAP determined pile resistance was 15 % greater than the pile resistance determined by DPDE. This finding confirms that in case of high pile resistances DPDE underestimates the pile resistance [2].

Expected length of production piles based on test piles

Figure 9 shows the elevation heat map indicating the toe level corresponding to required end-of-driving resistance. The black dots show the location of the test piles, and the red dots show the location of “dummy” piles. The elevation at which a “dummy” pile reached the required resistance was the same as the closest test pile and they were used to cover the entire pile deck area. As mentioned before the penetration resistance graphs created from the digitized driving journals were analysed in the excel spreadsheet to find the elevation at which the required pile resistance was reached. Using the required pile head elevation, the production pile lengths were calculated adding a robustness of 0.5 m to the so derived pile length. In the final step the pile lengths were rounded up to comply with the manufacturer’s pile length increment of 1 m.

Production pile installation – selected data

The installation of production piles started on 27 March 2023. Table 1 shows selected data from the production pile installation as of 25 March 2024. It is believed that the low percentage of broken piles is an outcome of the extensive pile testing campaign and the derived soil set-up factor. The difference between designed and as-built pile length of 5.3 % is also related to the manufacturer's pile length increment of 1 m. Assuming an average pile length extension of 0.5 m due to the manufacturer's pile length increment the difference between designed and as-built pile length could be reduced by almost 2 km.

Figure 10 shows an example of a pile installation overview beneath on of the 20 plates (Plate 4) designed for the project. The coordinate system is DKTM3. The fill of a marker denotes initial assessment of piles installation. Green fill denotes fulfilling the pile installation requirements in terms of pile resistance and placement. A few piles in the south-west corner of the plate had a yellow initial status because the piles were installed up to 0.5 m above the assumed top of the limestone elevation (see Figure 5). Since all these piles reached the required pile resistance and considering the uncertainty of the top of the limestone surface, all the piles were approved, which is denoted by a green border of the marker. Some piles located in the same corner had a red initial status because they were installed more than 0.5 m above the expected top of the limestone. For those piles the soil set-up factor was disregarded and the obtained pile resistance was compared to the required one. As presented in Figure 10 all those piles reached the required resistance even without the soil set-up factor, and, therefore, the green border was used for those piles. Four piles were broken during installation (marked with a cross). Replacement piles were installed at a distance of 2 diameters (centre-to-centre) and assessed as other piles. The same procedure was conducted for all 20 plates.

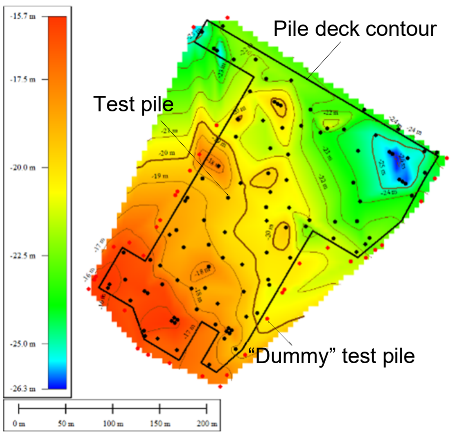

Figure 9 Expected pile toe elevation heat map.

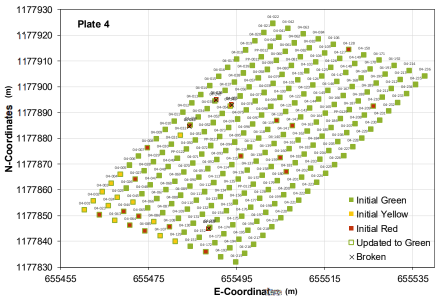

Figure 10 Overview of all piles installed beneath plate 4. Pile number is given above the mark.

Table 1. Selected data from the production pile installation.

Number of installed production piles	3989
Number of broken production piles	70
Percentage of broken piles [%]	1.8
Accumulated design length of installed production piles[1)] [m]	96287
As-built accumulated length of installed production piles[1)] [m]	91193
Difference between design and as-built pile length [m] ([%])	5094 (5.3)

[1)] Excluding broken piles

4. CONCLUSIONS

The following conclusions can be drawn from the present case study:

- The use of commercial and in-house made software greatly enhanced the design approach of large pile deck foundation and improve the efficiency during the execution phase of the project.
- The pile testing campaign allowed the use of a soil set-up factor > 1.5. This allowed a reduced demand on end-of-driving resistance which greatly reduced the percentage of broken piles during installation as excessive hard driving could be avoided.
- Building and handling big data base requires following predefined procedures and methods by a supplier and receiver of the data.

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