TANGENVIKA JERNBANEBRU, TEST PILING OF LARGE DIAMETER END BEARING PILES

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KEYWORDS

Large diameter end bearing piles, Test piling, Sustainable foundations, Composite steel/concrete piles, Fatigue.

ABSTRACT

Tangenvika jernbanebru (Railway Bridge) is to be completed in 2027, and will be Norway's longest railway bridge, 1026 meters. It is part of an upgrading of the railway line from Oslo to Hamar, reducing the travel time to under 1 hour, designing for double track and 250 km per hour, maximum speed.

It is a concrete bridge and consist of sixteen axes, where each span is 70 meters, but end spans are less, 60 and 56 m. The foundation of the bridge in the lake, will mainly rely on large diameter end bearing piles.

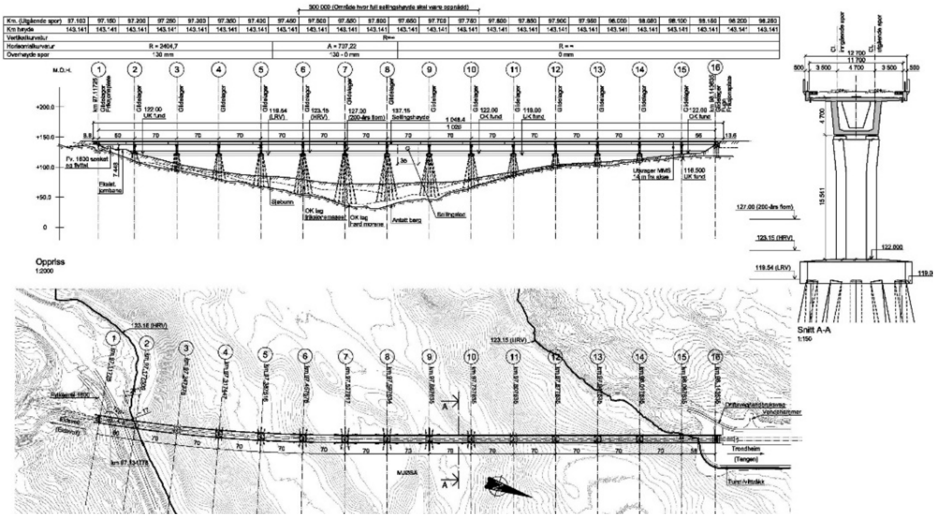

Figure 1 Tangenvika railway bridge, elevation, plan and section

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1 Bane NOR SF
2 Norconsult Norge AS
3 Implenia Norge AS

Driven steel piles with diameter 1430 mm will make the foundations at 5 axes in the middle, where the sediments over bedrock are thickest and the lake is deepest. Drilled steel piles of diameter 1016 mm will make foundations at 7 axes.

The piles will be concrete filled and are designed as composite columns according to Eurocode EN 1994-2.

Based on the soil investigations, there were significant uncertainties related to the pile driving process and bearing capacity for the driven piles. Due to the inclusion of the steel casing in the structural capacity, quite detailed information about pile driving was necessary for fatigue assessments.

Test piling for the driven piles were conducted in November 2023. This proved the drivability to be better than anticipated. The number of blows combined with stresses in the steel casings, estimated with PDA/CAPWAP, were acceptable in regards of fatigue.

Results further indicated that end-bearing capacity estimated directly with PDA/CAPWAP underestimated the bearing capacity by a factor of at least 4. This is believed to be related to the limited mobilization of end bearing capacity, due to small displacement (relative to the pile diameter) per blow of the hammer.

The test piles could be driven deeper than first anticipated and proved it possible to achieve a higher calculated bearing capacity. The pile foundations were optimised, reducing number of piles from 12 to 10 piles per axis in most axes, giving a reduction of ten piles in total. This equals close to 600 m reduced piles length, including sacrificial test piles, corresponding to approximately 2000-ton CO2-eqvuivalents.

This paper will in more detail present experiences from the test piling.

1. INTRODUCTION

Implenia Norge has taken on a design-build contract for Bane Nor, and Norconsult is Implenia's partner for designing the bridge, hereunder the piles.

Tangenvika jernbanebru will span across a bay in Mjøsa, Norway's largest lake. The railway will deviate from its previous route in the landscape, allowing for double tracks and curves that facilitate higher speeds.

The superstructure of the bridge will be made of prestressed concrete.
The substructure is founded directly on bedrock in axis 1 and 15. In axis 2 and 16 so-called steel core piles, "stålkjernepel[4]", are used.

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[4] "Stålkjernepel" is a widely used pile type in Norway, with a steel pile in the middle carrying the load, and a casing filled with concrete for protection against corrosion. The concrete is included in the buckling capacity.

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Axes 3-14 are designed with free-standing pile groups with large diameter end bearing piles. The large diameter piles in these axes are concreted steel pipe casings, designed as composite steel and concrete piles. The steel casings are designed to manage 10 mm corrosion over the service life of 100 years.

Drilled large diameter piles

In axis 3-4 and 10-14 the casings with diameter 1016 mm (28 mm and 40 mm thickness) are drilled to bedrock with RC-drilling (Reversed Circulation), mainly due to limited soil cover and low soil stability at some locations. The installation of drilled piles started in September 2023. For the drilled piles ring crowns and RC drilling system is used.

Driven piles

In axis 5-9 pile casings with diameter 1430 mm (34 mm thickness) will be installed by driving down to firm moraine or bedrock. The production installation of driven piles will begin in summer 2024. Test piling was conducted late in the autumn in 2023.

2. METHOD FOR EXECUTION OF TEST PILING

Pile testing was carried out with the aim of obtaining more information and basis related to:

- Driveability and driving resistance, especially through layers with uncertain and possibly high strength.
- Geotechnical bearing capacity, what can be demonstrated by dynamic impact testing (PDA/CAPWAP) and how this correlates with theoretically calculated static bearing capacity according to “Bearing capacity based on new empirical relationships against CPT” in chapter 4.2.1 in Peleveiledningen 2019 [3].
- Occurring driving stresses, stress interval and number of cycles define how much the steel tubes are subjected to the driving process in terms of fatigue.
- To provide a basis for developing a procedure for driving, stopping criteria and chiselling of the piles included in the bridge construction.

It was decided to place test piles near to axis 8 and 9. These test piles are horizontal piles and will not be used as a part of the permanent bridge. The piles were placed as near as possible to preliminary ground investigation boreholes.

The two test pile lengths were to be a minimum of appr. 80 meters near axis 8 and appr. 85 meters near axis 9. These lengths include the pile tip.

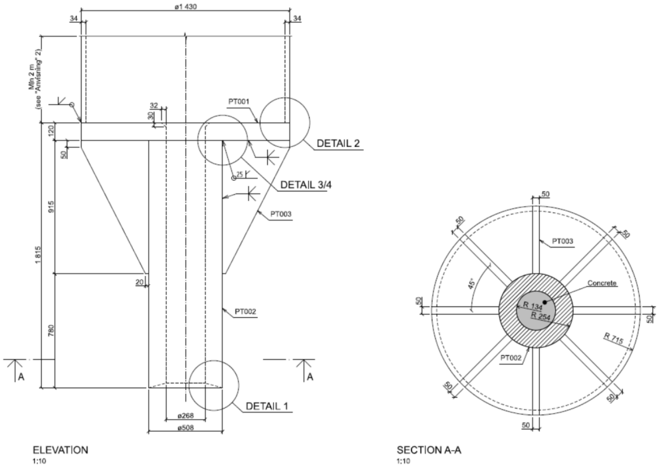

Figure 2 Dimensions of hollow concreted pile tip

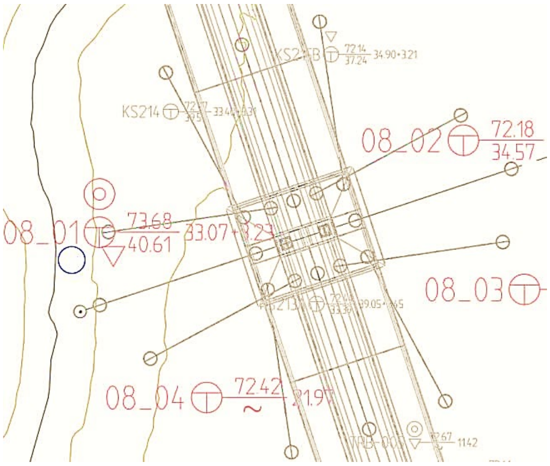

Figure 3 Test pile in axis 8 marked by the blue ring.

From the seabed, mapped with multibeam echo sounder, registered at approximately elevation +74.5, the interpreted layering can be summarized in axis 8 as:

- 0 - 7 m: Mud/clay/silt
- 7 - 26 m: Sand, with varying amounts of clay, silt, gravel, and small stones
- 26 - 34 m: Moraine
- 34 m: Bedrock - assumed to be of good quality

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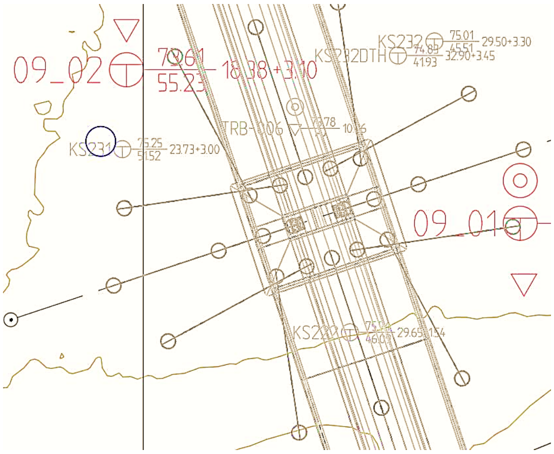

Figure 4 Test pile in axis 9 marked by the blue ring.

The ground conditions in axis 9 are briefly described, starting at the seabed at elevation +75,5 as:

- 0 - 6 m: Mud/clay/silt
- 6 - 22.5 m: Sand, with varying amounts of clay, silt, gravel, and small stones
- 22.5 - 24 m: Moraine
- 24 m: Bedrock - assumed to be of good quality

Hammer used for test piling

The S-350 Hydraulic Hammer is utilized for pile driving in the project. This hydraulic impact hammer is designed to provide high energy transfer during the pile installation process. It operates with an acceleration of 2g when set to full energy on the control panel. The hydraulic hammer's energy output is displayed on a monitor, allowing the operators to monitor and control the force applied to the pile during driving.

Pile driving procedure

The piles were driven water-filled to a minimum level with the water level in Mjøsa at the time of execution. To limit the size of tensile stresses occurring in the piles during driving, the supplied energy was gradually increased as the driving resistance increased.

3. GROUND INVESTIGATIONS AND RESULTS OF TEST PILING

Axis 8

Preliminary soil geotechnical investigations (borehole 08_01) is situated in a horizontal distance of only 5 m to the position of the test pile in axis 8. The depth to bedrock is assumed to be smaller in the location of the test pile com-

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pared to the borehole. The geotechnical investigations in borehole 08_01 included soil sampling and Cone Penetration Testing with pore water pressure (CPTu) executed by a sonic drilling rig on a barge.

The CPTu was performed with predrilling in between when the resistance was too large for further penetration due to risk of buckling of drill rods. The soil sampling showed that there was a clear relationship between significant amount of coarse gravel and/or cobbles in the sand layer and the need for predrilling. The size of this material was believed to cause an unrealistically high cone tip resistance (in regards of piling), due to the size relation to the cone (of size 15 cm^2). In borehole 08_01 there were at times registered tip cone resistance close to 50 MPa in the soil layer mostly believed to consist of medium dense to dense sand. The high tip resistance registered at times, gave uncertainties in how much resistance to pile driving these predrilled sections would induce.

The ground investigations also included the method that in Norway is referred to as total soundings. This is a method where a rotating drill bit is pushed into the ground with recording of force needed for penetration and penetration rate. When the force needed for penetration gets high enough the standard procedure is to first increase the rotational speed, then use flushing with water and eventually introduce the use of a top hammer. The method is therefore suited for drilling both in soil and bedrock. See also [5].

The registered blows per meter and average hammer energy utilized for the test pile, is compared with the soil investigation results in borehole 08_01 in Figure 5. As earlier stated, the depth to bedrock is believed to be somewhat shorter for the test pile, so the pile is assumed to be driven with the tip very close to bedrock or most likely partially with the tip on bedrock.

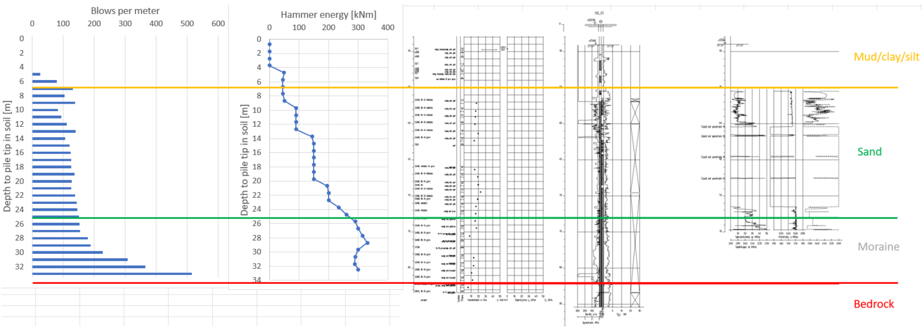

Figure 5 Blows per meter and average hammer energy compared with soil investigations in nearby borehole. Included interpretation of soil layering. Test pile axis 8

After self-penetration the test pile was instrumented for continuous PDA-measurements. The initial driving was carried out to a depth of approximately 31 m in soil before restriking and driving of the last 2 m was carried out 7 days later, to investigate the effect of time on skin friction.

Axis 9

There were preliminary ground investigations consisting of one total sounding. This is borehole KS231 situated in a horizontal distance of only 4 m from the position of the test pile in axis 9.

The registered blows per meter and average hammer energy utilized for the test pile, is compared with the total sounding performed in borehole KS231 in Figure 6. The depth to bedrock is believed to be somewhat shorter for the test pile, so the pile is assumed to be driven with the tip partially on bedrock after initial driving.

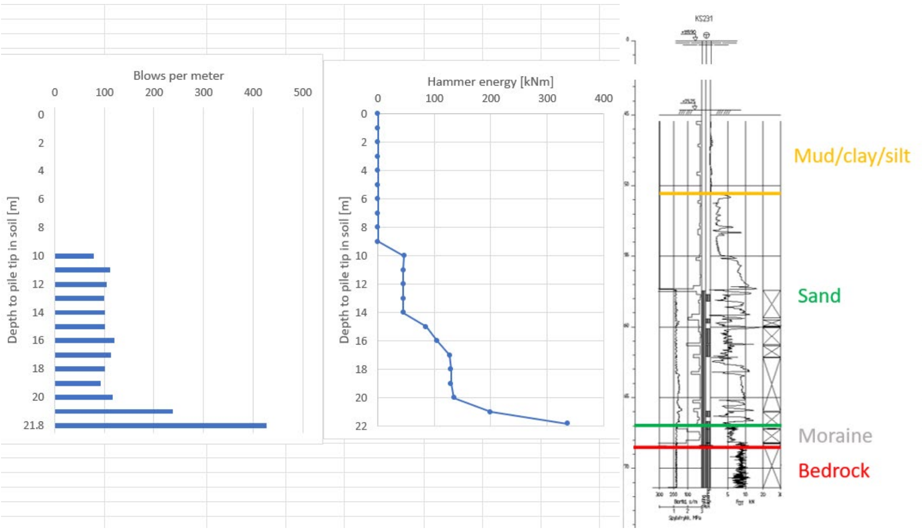

Figure 6 Blows per meter and average hammer energy compared with soil investigations in nearby borehole. Included interpretation of soil layering. Test pile axis 9

After self-penetration the test pile was instrumented using continuous PDA-measurements. After initial driving, restriking, and chiselling into bedrock were performed 2 days later. Displacement, hammer energy and accumulated number of blows versus chiselling depth are shown in Figure 7.

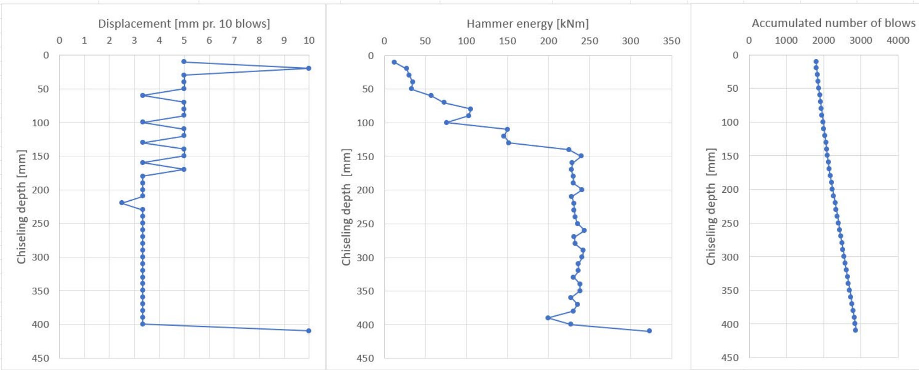

Figure 7 Displacement, hammer energy and accumulated number of blows versus chiselling depth into bedrock

4. INTERPRETATION OF RESULTS FROM TEST PILING

Axis 8

CAPWAP-analyses were performed on the PDA-data from single blows in various depths after the pile tip had reached what was assumed to be moraine. The estimated bearing capacity from skin friction and tip resistance is shown in Table 1.

Table 1 Estimated bearing capacity based on CAPWAP-analyses test pile axis 8

Pile length in soil [m]	Skin friction resistance [MN]	Tip resistance [MN]	Total resistance [MN]
25,5	4,5	3,9	8,4
28,5	5,9	3,2	9,1
30,5	7,6	4,6	12,2
32,5	11,1	10,6	21,7

The displacement per blow on the analysed blows are recorded to vary from approximately 2 mm to 7 mm. Due to the pile diameter being as large as 1430 mm the tip resistance is assumed to be highly underestimated according to [1] which states that "*a pile tip displacement up to 10 percent of the pile diameter may be required for full mobilizations in both sand and clay soils*". Further, it is recommended in [1] that the relationship between end bearing and displacement is assumed to be as shown in Figure 8. With 2 mm / 1430 mm = 0,0014 and 7 mm / 1430 mm = 0,0049, this gives Q/Q_p varying from 0,18 to 0,33 respectively. This equals to an expected tip resistance between 3 to 5 times larger than what was mobilized and thus estimated with PDA/CAPWAP.

z/D	Q/Q_p
0.002	0.25
0.013	0.50
0.042	0.75
0.073	0.90
0.100	1.00

Figure 8 Recommended end bearing – displacement curve according to [1]

Utilizing a method presented by Kjell Karlsrud at "Geoteknikkdagen 2023" [2] the actual end bearing capacity can be estimated more accurately from the CAPWAP-analyses. The CAPWAP-analyses estimate the distribution between skin friction and end bearing, but also the assumed distribution of the skin friction along the length of the pile. Unlike end bearing, skin friction is assumed to be close to fully mobilized.

The NGI99-method can be used for calculating the bearing capacity of a pile. The method is presented in [3]. Both skin friction and end bearing are determined based on tip resistance from Cone Penetration Test (CPT). When the skin friction is estimated from CAPWAP-analyses it is therefore possible to back calculate the corresponding tip resistance from CPT, q_{cCPT}. This is shown in Figure 9. The best fit to measured tip resistance with CPTU in nearby borehole is achieved combining the largest skin friction estimated with CAPWAP for the separate blows. The figure further shows the importance of having data on skin friction after restriking some days after initial driving for the best estimate. The recommended time for restriking for this purpose is 7-10 days as that is the time the full-scale tests (with measurements of bearing capacity) behind NGI99 apparently is based on.

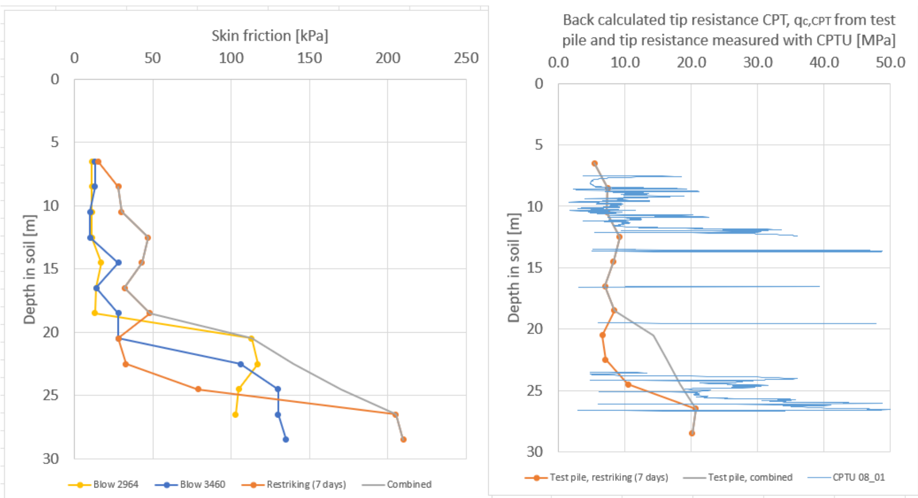

Figure 9 Distribution of skin friction estimated with CAPWAP and back calculated tip resistance $q_{c,CPT}$ compared to measured value from CPTU in nearby borehole

The back calculated $q_{c,CPT}$ can then be used to calculate the end bearing capacity based on the NGI99-method, as shown in Figure 10. In 25 m to 28 m depth, it is shown a tip resistance of 16-17 MN, which is at least 4 times larger than estimated directly with PDA/CAPWAP (Table 1). This fits surprisingly well with the mobilization curve shown in Figure 8 and the corresponding expectation of tip resistance between 3 to 5 times larger than estimated directly with PDA/CAPWAP due to limited mobilization of single blows.

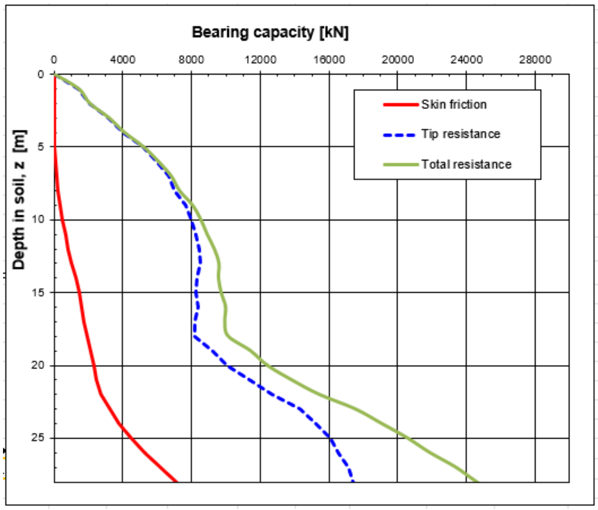

Figure 10 Calculated bearing capacity NGI99-method with back calculated $q_{c,CPT}$

With continuous PDA-measurements compression and tension stresses due to propagation of the wave from the impact of the hammer were estimated for the whole depth of pile driving. The largest compression stress was estimated at the end of pile driving with a value close to 180 MPa. The associated tension stress was approximately 40 MPa. At around 25 m depth, up to 80 MPa tension stress was estimated but the compression stress was at the same time somewhat smaller than maximum. Fatigue assessments according to [4] based on the estimated stress history on the test pile could be considered acceptable, so the steel casing could be utilized structurally after pile driving.

The test piling also proved that the drivability was significantly better than estimated with GRLWEAP before test piling. With attempts to back calculate number of blows and energy with GRLWEAP, a reasonably good fit was achieved with the use of soil resistance similar to what was calculated based on the NGI99-method and very low quake and damping values compared to what was determined with CAPWAP. The attempts at back calculating made it clear that for large diameter end bearing piles quake and damping factors determined with CAPWAP-analysis appear not relevant considering drivability. They seem only relevant for estimating which bearing capacity it is possible to estimate directly with PDA/CAPWAP.

Axis 9

CAPWAP-analysis were performed on PDA-data from control blows after chiselling into bedrock. The total bearing capacity was estimated to approximately 27 MN.

5. CONCLUSIONS

- Test implementation piling significantly mitigated risk and facilitated the optimization of pile design.
- The test piles demonstrated that they could be driven deeper than initially anticipated. This allowed for a higher calculated bearing capacity, optimizing the number of driven piles in each axis. Generally, the number of piles was reduced from 12 to 10, decreasing the total number of piles by 10. This equates to a reduction of approximately 600m in pile length (including test piles), corresponding to roughly 2000-ton CO_2-eqvuivalents.
- The skin friction estimated from CAPWAP can be used to back-calculate the cone tip resistance ($qc_{,CPT}$) with the NGI99-method. The back-calculated tip resistance aligns well with the tip resistance recorded with CPTU in the nearby borehole. In this manner, a test pile can supplement CPT/ CPTU tests for determining bearing capacity and drivability based on CPT tip resistance. This is particularly beneficial in soil layers containing gravel, cobbles, and boulders, where CPT is challenging to perform without significant predrilling. The recorded CPT tip resistance can sometimes appear unrealistically high in these soil conditions, complicating the assessment of a realistic bearing capacity and driving resistance based on CPT data. For this method, continuous PDA measurements at the depths of interest are highly recommended. Restriking (after 7-10 days) is crucial as the skin friction during driving is typically much lower than some time after, due to set-up effects.
- Interpretation of results from test piling indicate that end-bearing capacity estimated directly with PDA/CAPWAP underestimated the bearing capacity by a factor of at least 4. This is believed to be related to the limited mobilization of end bearing capacity, due to small displacement (relative to the pile diameter) per blow of the hammer. The factor will in general be smaller for smaller pile diameter, but the same method as shown in this paper may be used to estimate the actual end bearing capacity also for smaller end bearing piles.

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- The test piling proved that the drivability was better than expected. For large diameter end bearing piles quake and damping factors determined with CAPWAP-analysis do not appear relevant considering drivability in GRLWEAP. Much smaller values had to be used to achieve a reasonably good fit.

ACKNOWLEDGEMENT

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