Modelling of pile groups and implementations of the non-linear effects in structural modelling programs. - The interface between pile group and superstructure.

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ABSTRACT

As a part of a bypass road project in Denmark, three bridges were designed; the largest with a total length of ~200 m divided over 5 spans. Each of the four middle foundations consisted of 22-25 vertical driven precasted piles whereas the two end foundations consisted of a combination with vertical and inclined driven precasted piles.

The pile groups were modelled implementing the theory of P-Y, T-Z and Q-W curves. The superstructure was modelled in a structural FE program.

In general when modelling pile groups, the interface to the superstructure is often made with an assumption of modelling the foundation as six linear springs placed in the pile groups rotational centre, resulting in a more rigid and conservative design. For the present project an optimization of the interfaces between pile group and superstructure was made by implementing the non-linear effects for the pile-soil interaction into the structural program. Specifically this was done by modelling the piles as "vertical" beam elements with non-linear spring supports i.e. P-Y curves as well as Q-W and T-Z curves. Through an iterative process this resulted in a more soft foundation than in traditional analyses. A softer foundation leads to smaller applied forces for the design of pile groups and by that an optimisation of the pile design with fewer piles.

Keywords: Pile Groups, Pile-Soil Interaction, Optimisation of Pile Design.

1 INTRODUCTION

As a part of a bypass road project in Denmark, three bridges were designed; the largest with a total length of approximately 200 m divided over 5 spans. The project is a "design-and-build project" executed by the company Arkil A/S.

An overview of the bridge is given in Figure 1 and Figure 2. The bridge is to be built over a large water valley which is environmental protected meaning that restraints are put on the design and project when constructing close to the stream.

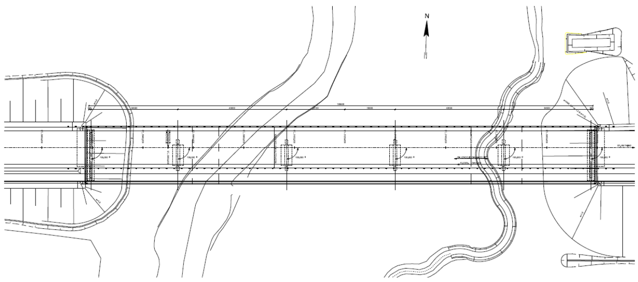

Figure 1: Overview of project - plan drawing

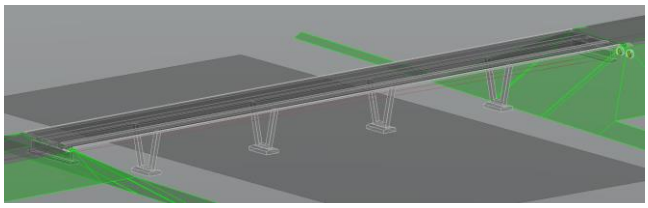

Figure 2: Overview of project - 3D model

Each of the four middle foundations consists of 22-25 vertical driven reinforced precasted piles whereas the two end foundations consists of a combination with vertical and inclined driven reinforced precasted piles. An illustration of the pile configuration for one of the middle foundations is shown in Figure 3.

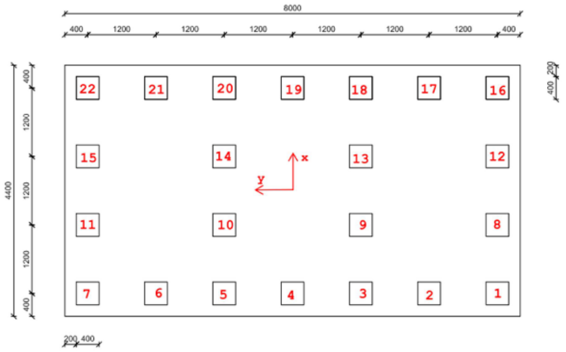

Figure 3: Illustration of pile configuration for one of the middle foundations.

The piles were designed to have a final penetration depth of approximately 15 m. In each pile group the piles have a c-c distance between 3-4 times the widths of the pile, meaning that pile group effects needed to be accounted for when dealing with lateral loading.

In Figure 4 to Figure 8 the construction of the bridge is shown.

Figure 4: Construction of the bridge – excavation for temporary foundations for scaffolding

Figure 5: Construction of the bridge – installation of piles

Figure 6: Construction of the bridge – installation of piles

Figure 7: Construction of the bridge – installation of piles for one of the middle foundation

Figure 8: Construction of the bridge – overview of the site

2 SITE AND GROUND CONDITIONS

The site investigations carried out within the site included both geotechnical borings as well as CPT's.

For each of the foundations a minimum of one boring and a CPT were executed to a depth of 17 to 25 meters below ground surface.

The borings shoved a large variation of soil deposits for the first 0.3-3.5 m with variations between sand/clay and peat. The peat was mostly discovered in the area close to the existing stream. Below the first 3.5 m the majority of the deposits consisted of meltwater sand with embedded layers of meltwater silt and sand till. Secondary deposits consisted of clay till. In Figure 9 a longitudinal soil cross section is seen.

The result from the CPT's shoved similarity with the geological descriptions from the borings.

Only some of the borings was drilled to the limestone reached between 12 m to 18 m depth below ground surface. The limestone is described as a weak material and therefore no refusal when driving into the material was to be expected. In the present analyses the limestone was treated as a frictional material.

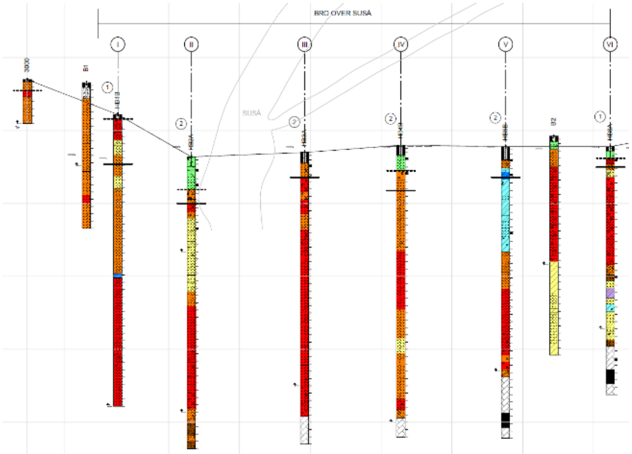

Figure 9: Longitudinal soil profile

For both end foundations and three of the middle foundations the piles were to be driven with pile tip into the meltwater sand while the last middle foundation had pile tip into limestone due to the limestone being reached at a higher level at this position.

Further the two end foundations were to be constructed in a man-made embankment consisting of gravel and sand. The embankments were constructed with a height of up to approximately 15 m.

Because of the specific ground conditions with the pile tip either into sand or into limestone, the bearing capacity for each pile needed to be verified by use of the Danish Pile Driving Formula as well as by use of PDA with CAPWAP for piles with pile tip into limestone.

It was seen that for two of the middle foundations with pile tip into sand, a majority of the piles achieved a much higher bearing capacity than anticipated. This was believed to be a result of compaction around the piles in the areas in which the sand deposits consisted of larger parts of sand till and coarser grains for the meltwater sand deposits.

3 DESIGN METHODS

In general when modelling pile groups, the interface to the superstructure is often made with an assumption of modelling the foundation as six linear springs placed in the pile group's rotational centre, resulting in a more rigid and conservative design in which the full capacity of the pile group is not computed.

For the present project an optimization of the interfaces between pile group and superstructure was made by implementing the non-linear effects for the pile-soil interaction into the structural program used for design of the bridge – in the present case LUSAS.

Through an iterative process it was believed that this would result in a more soft foundation than in a traditional analysis. A softer foundation leads to smaller applied forces for the design of pile groups and by that an optimisation of the pile design with fewer piles.

3.1 Finite Element Programs

Each foundation was calculated in Rambølls own structural FE analysis programme, ROSA. The inputs are the material properties for pile and soil, the geometry and the load cases. In Figure 10 is seen a computer model for one of the end foundations.

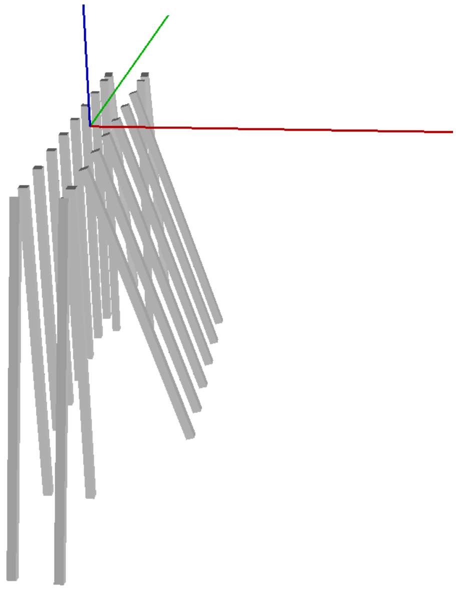

Figure 10: ROSA computer model for end foundation

In the FE-analysis the capacity of the soil and the interaction between soil and pile are determined in form of a set of non-linear soil curves/springs, as illustrated in Figure 11: .

- Lateral interaction. The P-Y curves are modelled by the procedure given in the API Standard.
- Axial Interaction. The T-Z curves for pile soil axial interactions are modelled by smooth curves.
- Tip Load Displacement. The Q-W curves for the tip load displacement relationship are assumed to be tri-linear for compression..

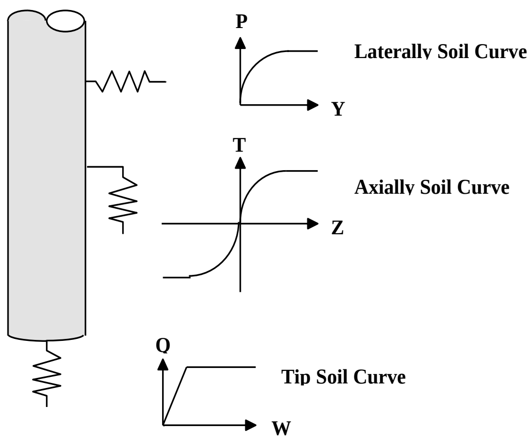

Figure 11Model of non-linear springs used in ROSA

The result is the calculated bearing capacities and the deformations as well as the forces along the pile. The effect from pile forming a group is accounted for according to Mindlin (1936).

To optimize the construction the derived load-displacement curves were implemented into the structural program used for the design of the bridge. Specifically this was done by modelling the piles as "vertical" beam elements with non-linear spring supports as illustrated in Figure 12.

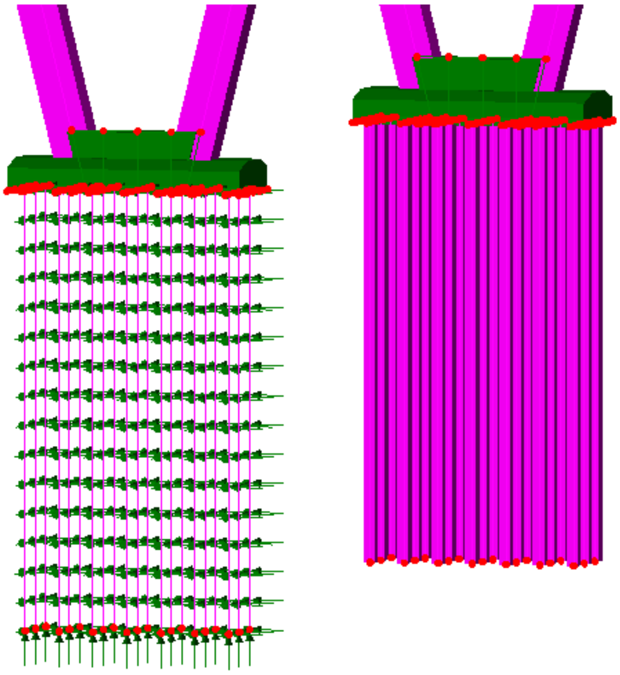

Figure 12Model of pile foundation in the structural FE-program for middle foundation

The process of the calculations was as the following steps:

1. The bridge structure is modelled with external loads and a fixed foundation.
2. Calculations are executed to find the bending moments and forces on the foundations as well as a first estimate of pile configuration.
3. The pile groups are calculated with the above found forces (& moments) as external loads and ends up with pile settlements and internal forces (shear, axial) and bending moments as well as load-displacements curves for each pile.
4. The structure is then recalculated with use of the load-displacements curves as entry data for the model resulting in a new set of forces (& moments).
5. Step 3 and 4 is then repeated

This procedure is an iterative loop, to be repeated until convergence is achieved between settlements (stiffness of bearings/piles) calculated by the structural program and ROSA.

4 RESULTS

Comparison was made for a conventional design without implementations of load-displacements curves in the structural program:

- Conventional design: 32 piles
- Implementation of load-displacements curves: 22 piles

It was found, that by implementation of load-displacement curves, a pile group would consist of approximately 2/3 of the number for the same case using conventional design methods.

5 CONCLUSIONS

It was found, that by implementing load-displacements curves in the structural program and performing an iterative optimization process is cost efficient. It takes that both the structural engineer as well as the geotechnical engineer needs to have an understanding for each other's work.

The process is more time consuming but it is the authors meaning that the extra time used in the design is quickly earned, especially when dealing with larger projects.

Further and important notice is, that because an implementation of p-y curves was introduced in the design, a pile group only consisting of vertical pile could be used as long as the lateral forces was not of a to high magnitude.

The economic potential in using this more advanced approach for optimizing pile foundations is evident especially for pile groups under large lateral loading.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

API. 2000. Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms Working Stress Design. American Petroleum Institute API-RP2A-WSD, Rev. 21st edition

Mindlin, R.D 1936. Force at a point in the interior of a semi-infinite solid. Publishing firm Appel. Phys. Vol. 7.

ROSOIL, RAMBØLL´s Program ROSOIL, Pile soil curves. User’s Guide Latest edition.

ROSAP, RAMBØLLs Offshore Structural Analysis Program Package. User's Guide Latest edition.

LUSAS. Engineering analysis software. Finite Element Analysis.