Drilled-pile wall for deep excavation at Frederiksberg Station, Copenhagen

Rideau de pieux foncés pour une excavation à la Station Frederiksberg, Copenhague

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ABSTRACT: Deep excavation at a densely populated area is always a difficult task. In this paper the design and performance of a pile wall for a deep excavation in the centre of Copenhagen city is presented. Here it was possible to use drilled pile wall, a very flexible pile wall instead of a stiff concrete diaphragm wall. This solution is very economical and very competitive with other methods. The use of the FEM method with Plaxis makes it possible to design the optimal configuration of anchors and pile wall.

RÉSUMÉ: Une excavation profonde dans une région à population dense est toujours une tâche difficile. Dans cet article, le design et la performance d'un rideau de pieux pour une excavation profonde au centre da la ville de Copenhague est présenté. Il fut ici possible d'utiliser un rideau de pieux foncés, un rideau très flexible comparativement à un rideau rigide en béton. Cette solution est très économique et très compétitive comparée à d'autres méthodes. L'utilisation de la méthode des éléments finis (FEM) à l'intérieur de Plaxis rend possible le design optimal de la configuration des ancrages et du rideau de pieux.

1 INTRODUCTION

Construction of Copenhagen's mini-metro began in early 1997. Built both over and under ground with a total length of about 20km, the section passing under the centre of Copenhagen consists of two bored tunnels, each 8 km long together with other underground constructions such as stations, shafts and cross-overs. The total cost for the Metro is more than $1bn. The metro will be completed Year 2004. Three tunnelling methods are being used: TBM (*Tunnel Boring Method*), NATM (*New Austrian Tunnelling Method*) and cut and cover. TBM is being used for the main part of the metro, approximately 7.4km. Cut and cover is used where the tunnel meets the ground, such as at Frederiksberg Station.

2 PROJECT DESCRIPTION

The pile wall is at Frederiksberg, one of the underground stations in the centre of the city, see Fig. 1. The tunnel and station is constructed by cut and cover method and the excavation for the project is more than 200m long, 8 to 12m in depth and 25 to 30 m in width.

Fig. 2 shows an overview of the project. To the north side of the excavation (right side of the figure) lies a new shopping precinct, Frederiksberg Centre, which is a quite heavy five-storey building located only 0.3m from the pile wall. Vertical and horizontal displacements of the building are restricted to 5 mm by the client. To the south of the project (left side of the figure) is the Old Frederiksberg station. Built in 1864, it is the oldest railway station in Denmark and had to be protected during the construction of the metro. These two existing buildings made the excavation a very difficult and challenging foundation-engineering project.

3 GEOTECHNICAL CONDITION

The ground surface level is approximately +11.5m. The soil profile includes a fill layer of 0.5 to 1 m thick, an upper clay till layer of 4m to 7m thick, a sand or sand till 2m to 4m thick and a lower clay till layer of 6m to 7m. The clay till is heavily over-consolidated and has a c_u value between 150kPa, for the upper layer, and 300kPa, for the lower layer. The limestone occurs at level –4m to –6m.

The modulus of compressibility of the clay till and sand till layers increases with depth and depends on the vertical effective stress. Groundwater level is +2.5 m, i.e. 9 m below the ground surface. The characteristic values of soil parameters are shown in Table 1, in which σ'_z is effective vertical stress and K oedometer modulus.

Table 1. Soil parameters – characteristic values

No	Soil type	Density (kN/m^3)	c_u (kPa)	ϕ' (°)	K (MPa)
1	Fill	18-20	0	30	15
2	Upper clay till	21-22	150	33	$10+1500\sigma'_z$
3	Sand till	21-22	0	38	$10+1500\sigma'_z$
4	Lower clay till	22-23	300	35	$10+1500\sigma'_z$
5	Limestone	21-22	-	40	100-200

Figure 1. Location of Frederiksberg Station and the Metro in Copenhagen city.

4 DRILLED PILE WALL

Soil conditions combined with the environmental requirements for a very densely populated area in the centre of Copenhagen made the excavation a very difficult task. The original proposal was for a stiff concrete diaphragm to support the excavation, which was very expensive and would have cost about $5.5M. Besides, in many places there was no space for a diaphragm wall, especially at the Frederiksberg Centre. One suggestion was to move the Old Station and then replace it back after construction was completed. This would have cost about $2M.

Figure 2. Overview of the excavation. To the right is Frederiksberg Centre, and to the left the Old Frederiksberg Station.

Stabilator AB, nowadays Skanska Foundation, proposed a quite flexible and very economical solution: a drilled pile wall. Each pile consists of a steel tube 194mm in diameter and 6.3 mm thick and a steel HEB-beam. Piles are spaced at 1m and the space between the piles is shotcreted. Earth pressure is transferred to the piles through the shotcrete arch. The pile wall is supported by injected cable anchors of type Supa-lina cable with a declination of 30° to 35° spaced at 2m to 4m. The anchors, founded in granular material, had a length varying between 12m and 18 m, and an average fixed length of 6m. Two or three anchor levels were applied.

The method chosen to support the Old Station comprised a steel core instead of the HEB-beam to increase in the vertical bearing capacity of the piles. The Old Station was then supported by a beam system connected to the foundation wall and anchored to the limestone by vertical GWS anchors. The piles under the building will function both as sheet piles as well as underpinning piles, see Figure 3.

The drilled pile wall is installed as follows:

- A steel casing is drilled down. Casing segments are jointed by welding, as required.
- The casing is flushed by clean water.
- A steel H-beam or a steel core is inserted into the casing and drilled further into the limestone. The H-beam segments are jointed by welding, while the steel core by API-joints.
- The space between the H-beam or steel core and the casing is filled with concrete.
- Excavation is done down to the first anchor level. The soil surface exposed must be sufficient small so that soil will not move into excavation.
- The space between the piles is covered by shotcrete, 50mm thick, with or without reinforced steel net.
- The wailing is H- or double U-beam of steel.
- Tie back anchors are installed using standard anchor installation procedures. The anchors are tested and given a permanent pre-stress load.
- Excavation down to the next anchor level is made.
- The above steps are repeated as required until final excavation level is reached.
- Horizontal drainage wells are installed as required between the casings. Vertical drainage wells ("bleeding wells") are installed at the excavation bottom, or above the bottom, in order to avoid hydraulic uplift of impervious clay layers below the excavation level.
- The permanent tunnel structure is constructed. The groundwater level in the excavation is kept at the excavation level by means of pumping from that level. The discharge water is treated as specified in the tender documents.
- Back filling and removal of anchor pre-stress forces takes place. The drilled pile wall is cut 2 m below street level.

Soil anchors drilled into the sand layer were applied. Active design, a design concept based on field measurement or observation, was used in order to define the anchor length, as well as shotcrete type. More than 400 anchors with a total length of 7600m were installed.

About 50000m^3 soil was excavated. The drilled pile wall with a total area of 3800m^2 and 6200m pile was completed within eight months.

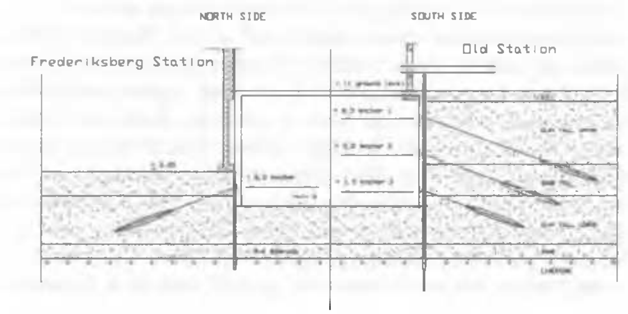

Figure 3. Section 3.198. To the left is Frederiksberg Centre, and to the right the Old Frederiksberg Station.

5 EUROCODE 7 AND THE DESIGN

Eurocode 7 was used for the design. The ULS (ultimate limit state) and SLS (serviceability limit state) analyses are considered. Two separate calculations have to be performed for ULS, one for case B and another for case C.

The aim of Case B is to provide a design that is safe against deviations of characteristic value of Actions (loading, effects of the loading), when the soil strength parameters are equal to their characteristic values. This calculation ensures the sizes and the strength of the structure against ULS if the loading are more unfavourable than expected while the soil shear strength is closed to its expected value.

The aim of Case C is to provide a design which is safe against unfavourable deviations of characteristic soil strength parameters and against uncertainties associated with the geotechnical calculation model, while the permanent loading, including the soil weight, is equal to its characteristic value and the variable load is slightly factored. This calculation ensures the sizes and the strength of the structure against ULS if the soil parameters and the soil models are worse than expected while the loads are closed to their expected value.

The aim of SLS analysis is to predict the real displacements both of the soil and geotechnical structure. In this analysis, unit partial safety factors are applied on the soil properties while the load is estimated as the regular combination or the rare combination.

The partial factors for different calculation cases are shown below in Table 2. The partial coefficient for deformation, both the modulus of compressibility and its increase with depth, is taken as 1.2. Therefore, for all sections three different cases according to Eurocode 7 were analysed: the ULS case B and C, and the SLS with the rare combination load case.

The calculation results from the ULS analysis were used for determining the dimensions of the pile wall structure. The soil displacements from the SLS analysis were used for adjusting the possible damage for the existing buildings nearby.

Table 2. Partial safety factors according to Eurocode 7 part 1

Case	Actions			Soil properties			
	Permanent		Variable				
	unfavour.	favour.	unfavour.	$tan\phi'$	c'	c_u	q_u
A	1.00	0.95	1.50	1.10	1.30	1.20	1.20
B	1.35	1.00	1.50	1.00	1.00	1.00	1.00
C	1.00	1.00	1.30	1.25	1.60	1.40	1.40

6 FINITE ELEMENT ANALYSIS

FEM analysis was carried out with PLAXIS, Version 7.1 (Finite Element Code for Soil and Rock Plasticity), a program developed by Plaxis BV and Delft University, the Netherlands. In all six different sections have been calculated. Three FEM analyses have been made for each section. Two most critical sections, the pile wall along the Frederiksberg Centre and the wall below the Old Station at the South side are described below.

Calculations were carried out by choosing the plane-strain analysis with 15-noded elements. A Mohr-Coulomb model and drained material were used for simulating the soil. The sheet-pile wall is modelled by the structure elements. Between the structure elements and the soil elements, interface elements are used. The anchor is modelled by the node-to-node anchor elements, while the grouting body of the anchors is modelled by the geotextile elements together with the interface.

For drained analysis a free water level of +2.5m was assumed. The pile wall is not watertight, so the ground water can flow through it. In the analyses all the staged constructions are simulated.

In traditional sheet piling or retaining wall, it is commonly assumed that the soil is *active* behind the wall and *passive* in front. Different (active and passive) soil properties were first suggested to use for simulating a anisotropy problem, which can be a inherent anisotropy or a stress induced anisotropy, see Ladd & Foott (1974). The first one is the result of major difference in soil structure, which occurred during formation of the soil. And the second results from rotation of principal stresses during shear and variation in the intermediate principal stress. However, it should be noted that with anchor prestressing loads, the classic concept of Rankine active and passive sides is not longer correct. In reality, the soil behind a pre-stressed anchor at the so-called active side according to the Rankine concept will behave passively. The same shear strength parameters should therefore be used for soil both behind and in front of the wall in FEM analysis.

7 DESIGN OF PILE WALL ALONG FREDERIKSBERG CENTRE

One of the most critical parts of the project is the pile wall along Frederiksberg Centre, a heavy retail building located only 30cm from the sheet-pile wall, see Figure 3. The load from the Frederiksberg centre used for the calculations is very large: 516 kN/m for ULS case B. Despite this large load, the client required the soil displacements under the foundation to be less than 5 mm. To meet this firm requirement, a very high prestressing anchor force was used. The staged constructions are simulated with the following steps:

- Simulate the existing foundation (foundation wall and basement floor) and reset displacements to zero
- Excavate to the level of the existing foundation +3.5m
- Install the pile wall and excavate to +2.5m
- Install the anchor with a prestress load
- Excavate to the final level of the excavation bottom, -0.5m.

The results show that the displacements of the Frederiksberg Centre foundation in all the construction stages would be very small, less than 1 mm for horizontal displacements, and less than 5 mm for settlement (vertical displacements), see Fig. 4. The angular distortion, which is estimated for a structure span of 7m, is about 1/1400. These values are accepted by the client. Measurement eight months after completion of the excavation showed that the maximum settlement and horizontal displacement of the foundation were both less than 1 mm.

In order to compare with the FEM analysis for this section, two traditional calculation methods were used: the analytical Rankine method, and the line-polygon method, which is often used in engineering practice. These two methods can not predict the soil movements, only the maximum bending moment in the pile wall and the anchor axial loads were therefore calculated. The bending moment obtained from FEM analysis M_{max} = 42 kNm/m (case B) and 49 kNm/m (case C) are comparable with the values obtained by the traditional methods. Using a reduction factor suggested by Rowe (1952), the Rankine method gave the maximum bending moment M_{max} = 54 kNm/m (case B) and 55 kNm/m (case C), and the line-polygon method, 57 kNm/m.

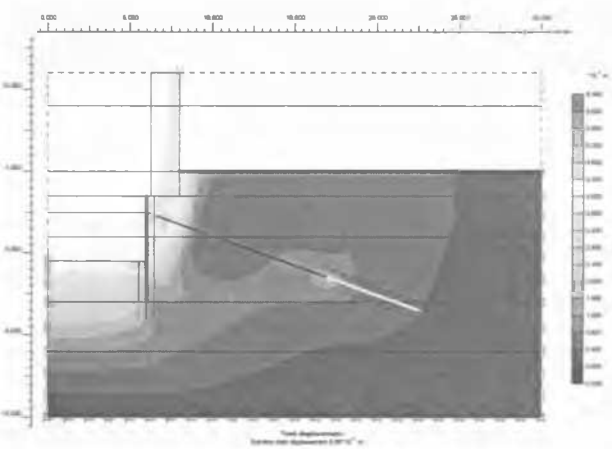

Figure 4. Total displacements – Pile wall along Frederiksberg Station

8 DESIGN OF THE PILE WALL UNDER OLD STATION

Another difficult part of the project is the pile wall under the Old Station. In order to protect the Old Station, it was first suggested to be moved and replaced back after completion of the construction. However this suggestion was too risky and expensive. To avoid moving the station the pile wall was used with two functions: to act as a wall and to underpin the structure. A part of the Old Station is hanged on the pile wall with the help of a beam system that is anchored to the limestone, see Figure 3.

The staged constructions are simulated with the following steps:

- Simulate the existing foundation and reset displacements to zero
- Install the pile wall, beam system and the tieback anchor
- Apply the house load and prestress the tieback anchor
- Excavate to Level +8.5m
- Install and prestress the first anchor
- Excavate to Level +5.0m
- Install and prestress the second anchor
- Excavate to Level +1.5m
- Install and prestress the third anchor
- Excavate to the final level of the excavation bottom, 0.5m, and i.e. 12m deep.

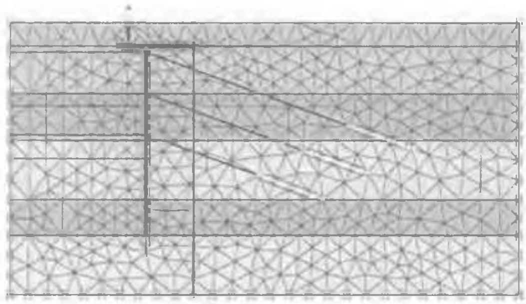

Figure 5. Element mesh – Pile wall under the Old Station

Figure 5 shows the FEM mesh for the analysis of the pile wall under the Old Station. The calculation results show that the maximum bending moment in the pile is 35 kNm/m. Soil displacements are quite small: the maximum horizontal displacement is 5 mm, while the max settlement of the foundation resting at the pile top is less than 1mm. Measurement eight months after completion of the excavation showed that the maximum settlement of the foundation was less than 1 mm.

9 CONCLUSIONS

The project demonstrated that it was possible to use drilled pile wall, a very flexible wall instead of a stiff diaphragm wall in the clay till conditions of Copenhagen. The resulting savings in time and cost were considerable.

The use of the finite element method with Plaxis makes it possible to design the optimal configuration of anchors and pile wall. In very difficult cases where deformation requirements are critical, FEM is a very effective tool for predicting deformations and displacements. This can be seen especially in the design of the pile wall along the Frederiksberg Centre.

Although the pile wall is quite slender the maximum bending moment is far from reaching the ultimate pile bending resistance. At the wall along the Frederiksberg Centre, the maximum bending moment was approximately 50 kNm, while the ultimate pile bending resistance was around 130 kNm, considering the combined contribution of the steel tube, the HEB beam and the filling concrete. If the composite interaction is taken into consideration this resistance is even higher. From full-scale model tests made by Stabilator, an ultimate bending capacity about 160 kNm was obtained. This is in very good agreement with the results from a FEM three-dimensional analysis using 3D FEM program Abaqus.

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