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Design of Retaining Walls at Metro Nordhavn, Copenhagen

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ABSTRACT

Zûblin A/S is a part of the MetNord JV who design and construct the Metro Cityringen – Branch off to Nordhavnen. The project consists of the Nordhavn Station, a Cut and Cover tunnel, a ramp which takes the trains up to ground level and a bored tunnel from Nordhavn Station to Østersøgade, where it is connected to the Cityringen Metro. Züblin A/S has been responsible for the design of the temporary structures which is mainly carried out as multiple supported secant pile walls, supported by pre-stressed ground anchors.

The first design was carried out by modelling the secant pile walls with SPOOKS which uses the theory of J. Brinch Hansen, commonly used in Denmark, for the ultimate limit state and the finite element program Plaxis for the serviceability limit state. Due to the limitation of Brinch Hansen's theory and discussions about stress-strain compatibility, the Employer doubted that the deformations necessary for activate active and passive earth pressure were sufficient in the ultimate limit state. Therefore the final design ended up being a combination of SPOOKS for the ultimate limit state and a PLAXIS model for ultimate limit state to verify the results of SPOOKS and a serviceability limit state calculation also with PLAXIS.

This paper tries to investigate the influence by introducing PLAXIS into an ULS calculation by making different variations of inputs that changes the stiffness of the system and thereby influences the stress-strain compatibility. The results will be compared with the results found with Brinch Hansen theory and discussed.

Keywords: Retaining walls, Brinch Hansens earth pressure, SPOOKS, PLAXIS, parameter study

1. INTRODUCTION

As a part of the Metro Cityringen in Copenhagen the Joint Venture (MetNord JV) consisting of Züblin and Hochtief are building the first part of the branch off to Nordhavnen, consisting of an underground Station, a Cut & Cover tunnel and a Ramp going up to the surface level and ending as an elevated track, see Figure 2.

The retaining walls for the underground Station are made as permanent secant piles supported mainly by 3 layers of temporary pre-stressed ground anchors. The retaining walls for the Cut & Cover tunnel are temporary secant piles supported by 1 or 2 layers of pre-stressed ground anchors. The Ramp area consists of permanent sheet piles supported by 1 layer of permanent pre-stressed ground anchors.

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The deepest excavation, where the TBM drive will start, is around 18 meter deep and decreases along the entire alignment towards the end of the ramp section.

This paper will focus on the design of the secant pile walls of the underground Station and the Cut & Cover Tunnel in the temporary situation, where one cross section will be used for the analyses carried in this paper. The secant piles installed have a diameter of 1.2 meter and c/c distance of 0.9 – 1 meter and reinforced by reinforcement cages. The wall is used as cut off wall for the ground water and is therefore drilled and casted until level -20 (DVR90), with reinforcement going to the toe of the pile.

2. DESIGN OF RETAINING WALLS

The secant piles are designed in both ultimate limit state (ULS) and serviceability limit state (SLS). In Denmark, the ULS calculation is mostly carried out in the program SPOOKS, which uses the earth pressure theory developed by J. Brinch Hansen, (Hansen J.B, 1953). His theory is using a combination of zone and line rupture where the earth pressure distribution is a modified compared to normal failure mechanism and depending on the rotation of the wall. The theory states, that the necessary displacement to mobilize active and passive earth pressure will be present independent of the failure mechanism of the wall. The failure mechanism from the theory of Brinch Hansen is only a statically possible solution, if $\varphi > 0$, meaning it is a lower bound solution.

From SPOOKS it is possible to obtain anchor forces, bending moment, and necessary toe level to fulfil the equilibrium requirements.

The program has certain limitation, as it is only possible to include one real support force. When designing multiple supported walls, it is then necessary to add some of the anchor levels as, so called, additional pressures. As the values for the additional pressures, in principle, can be chosen arbitrary it is necessary to check if the anchor force chosen is feasible compared to the earth pressure distribution. This can be done with a simple beam calculation, where the anchor levels are modelled as simple supports and the earth and water pressure is applied as a line load.

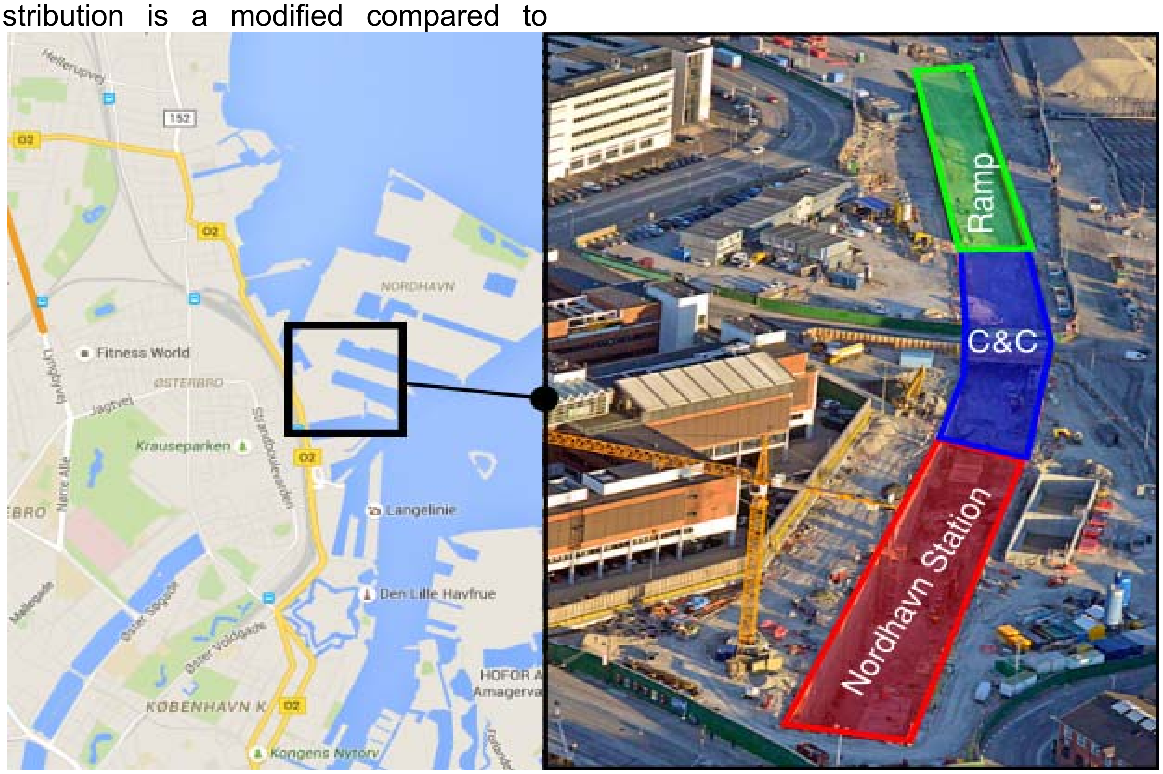

Figure 1.Location of the new underground Nordhavn Station, Cut & Cover tunnel and Ramp

Due to the fact that the program does not take soil-structure interaction into account, the Employer was concerned that there is insufficient compatibility between stresses and strain meaning that the deformations necessary to mobilize full active earth pressure is not present and the program therefore calculate too small section and anchor forces.

Different approaches was used to convince the Employer that the design carried out was sufficient, but without luck. Therefore it was decided to model the wall and anchor with Finite Element, by means of a PLAXIS model. With the PLAXIS model it is possible to include all construction sequences, wall and soil stiffeners, and therefore also built-in forces coming from pre-stressing of anchors and from the different excavation stages.

3. SOIL AND GROUND WATER CONDITION

The following soil and ground water conditions are used for the calculations in this paper.

3.1. Soil condition

The boreholes made on the location shows fill layers with a thickness variating from 3.5 to 11 meter. That matches the fact that it is an old backfilled harbour area. Below the fill a 2.5 to 10 meter thick clay till layer with lenses of sand till and melt water sand is registered on top of the limestone. The top level of the limestone varies throughout the area and has a glacially disturbed zone of around 1-3 meter. A 2 meter disturbed limestone zone has been used in the design. The soil profile used in this paper is shown in Figure 3.

The characteristic drained strength parameters used for the calculation are shown in Table 1.

3.2. Ground water level

In the design of the retaining walls, a primary and secondary ground water table are used. For simplification only one ground water level is taken into account in the analysis, which is positioned at ground level.

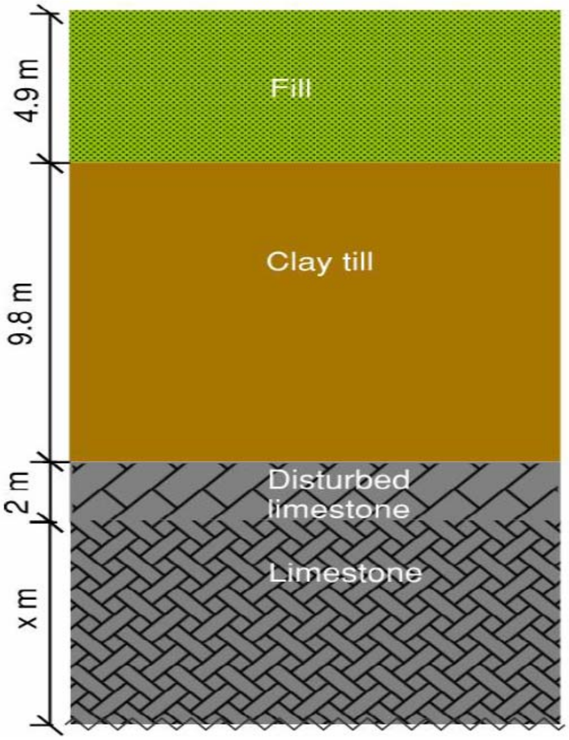

Figure 3.Soil profile used for the calculations in this paper

Table 1.Soil properties used for the MetNord project and calculations in this paper

Soil layer	γ/γ'_m	φ'	c'	E_{oed}	v
	kN/m^3	°	kN/m^2	MN/m^2	-
Fill	17/19	30	0	3	0.3
Clay till	22/22	34	20	12+1500xσ'_{red} 1)	0.3
Dist. Limestone	22/22	45	50	750	0.25-0.30
Limestone	22/22	45	100	900	0.25-0.30

1) σ'_{red} is the vertical effective stress corresponding to the minimum stress level the soil has experienced

4. SPOOKS CALCULATION

For the investigations in this paper a SPOOKS calculation of a cross section at the station is included. The section has two anchor levels and an excavation depth of 17.5 m. Figure 4 shows the results at the final excavation stage giving the bending moment, anchor force and necessary toe level.

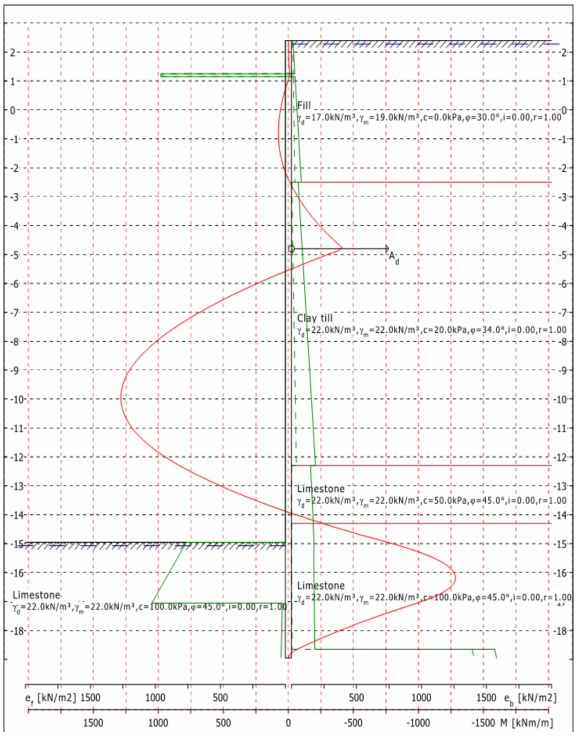

Figure 4.Graphically output from SPOOKS

The results are listed in Table 2.

Table 2.Design values from SPOOKS calculations

Bending moment	[kNm/m]	1287
Upper anchor load	[kN/m]	196
Lower anchor load	[kN/m]	868
Toe level	[m]	-18.95

The Spooks calculation shows a field bending moment which is identical to the embedment moment.

5. PARAMETER STUDY

When introducing PLAXIS into an ULS calculation, it gives many options and different inputs that can be adjusted. For the secant piles at MetNord a number of inputs will have an influence on results. That is:

- Stiffness of the wall – cracked or uncracked concrete properties?
- Stiffness of the soil layer in this case the clay till
- Interface reduction factor, R_{inter}.
- Over-consolidation ratio
- Type of soil model – Mohr Coulomb or Hardening Soil?
- Pre-stressing level for the anchors

A sensitivity study of the different parameters have been carried out with focus on anchor load and bending moment. The different investigation is done on the same model and with the same reference result to compare with. The results of the SPOOKS calculation from section 4 are included in the comparison. **Eroare! Fără sursă de referinţă.** shows the PLAXIS model used in the investigation. The pre-stressed ground anchors are modelled as node-to-node tension elements for the free length and the bond length is modelled as geogrid element. The upper anchor layer is installed with an inclination of 30° and lower anchor layer with 40°. The secant pile wall is modelled with plate element with elastic properties. The characteristic surface load is 20 kPa.

After each main excavation steps an ULS step is calculated. This is done with a Phi-C reduction with a target value of 1.32 and an increased load to the design load of 30 kPa, which correspond to the partial safety factor for the effective soil parameters. A Mohr-Coulomb material model with drained parameters is used for all soil layers. The influence on the deformations will not be considered in this paper.

5.1. Stiffness of wall

For the stiffness of the wall the Employer required that the stiffness of a cracked section is used. The argument was that using a cracked stiffness of the wall the calculation would give higher anchors forces but less bending moment in the wall. To see what influence it would have to use a cracked or uncracked bending moment, the influence of the wall stiffness is investigated. The bending stiffness, EI, is increased with intervals of 100E3 kNm^2/m, starting from 600E3 up to the double, 1.2E6 kNm^2/m, corresponding to a wall 4-5 times stiffer than the largest AZ - sheet pile profile on the market. The results of the analysis are shown in Figure

6; the positive bending moment is from the embedment in the soil, while the negative bending moment is the field bending moment towards the excavation pit. The tendency of the results is as expected – almost no change occurs.

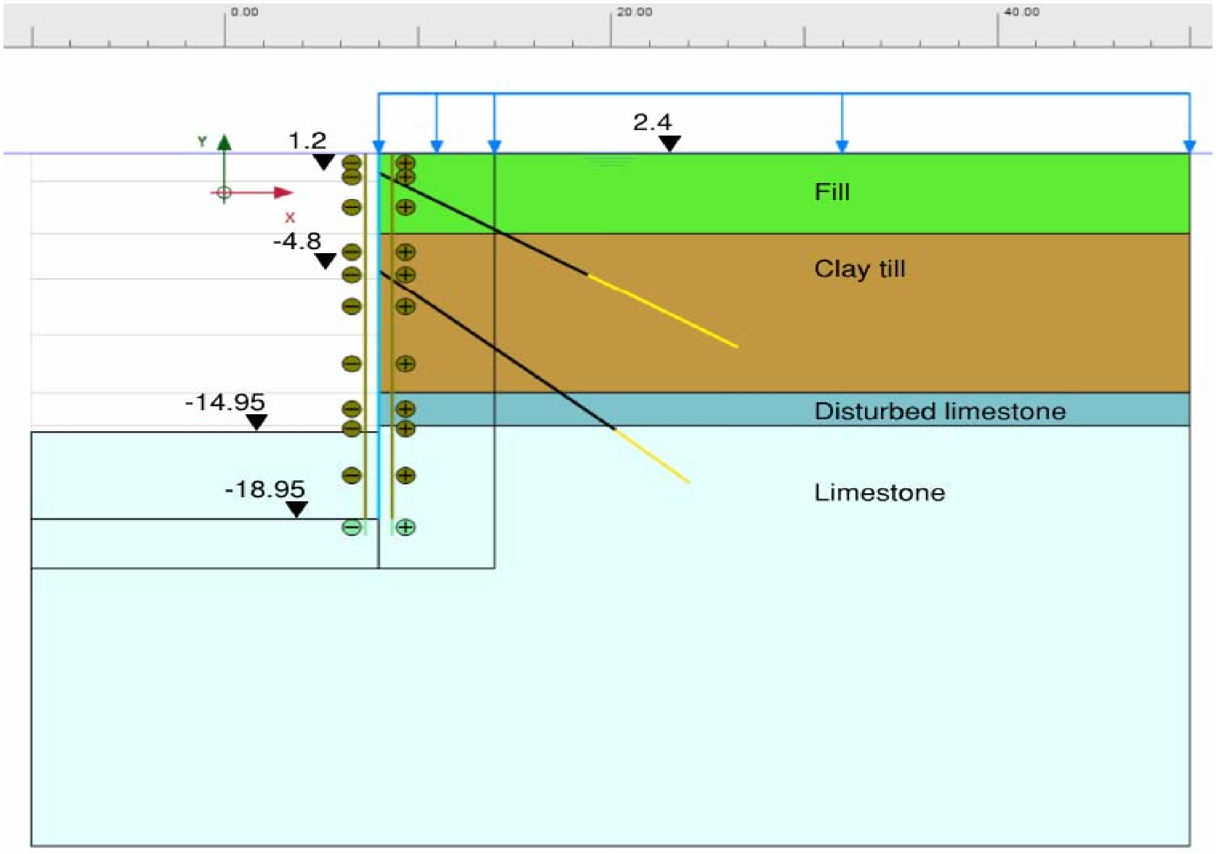

Figure 5.Plaxis model used for the different analyzes

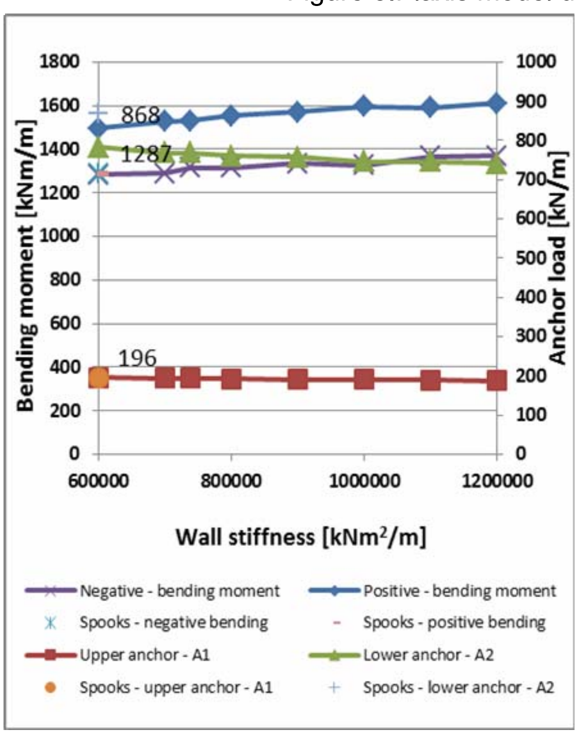

Figure 6 Comparison of results with different wall of the analysis

The increase in stiffness of 100% gives an increase of approx. 7.7% for the positive bending moment and 6.6% for the negative bending moment. The decrease in anchor load is at the same time 4.2% for the upper anchor layer and 5.2% for lower anchor layer. It is therefore only have marginal and neglectable influences which wall stiffness is used, so the difference in using cracked or uncracked stiffness would only be marginal for the design.

5.2. Variation of clay till stiffness

The stiffness of the clay till is derived from a number of oedometer tests. The Danish practice for presenting the oedometer modulus is by following equation:

$$E_{oed} = a + b \times \sigma'_{red}$$

In this way it represents the in-situ conditions after a pre-consolidation and an unloading to σ'_{red}, which is the minimum effective vertical stress the soil have experienced after the pre-consolidation. The chosen E_{oed} for MetNord is found by comparison of other clay tills in the Copenhagen area and the Great Belt Link, as shown in Figure 7.

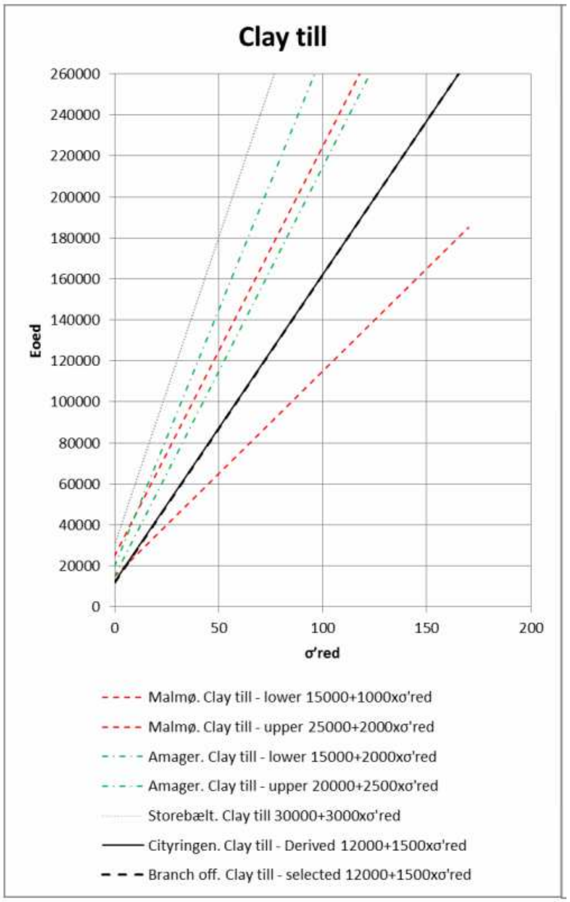

Figure 7.Compiled oedometer modules for different locations

The chosen value is also compared to measured values from oedometer tests carried out on site, and shows that the chosen value is conservative. By introduction FEM in an ULS calculation it means that the stiffness of the surrounding soil will have influence on the section forces and anchor forces. Therefore an analysis with the different E_{oed} values from Figure 7 is carried out. To take into account the increase of stiffness with the depth (effective vertical stresses), the E_{inc} function in Mohr-Coulomb model is used. The relation between E and E_{oed} for MC is given by:

$$E = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} E_{oed}$$

The poissons ratio, v, for the clay till is 0.3. It is only the stiffness which is changed; the effective strength parameters are not changed. The results of the analysis are shown in Figure 8 and Figure 9. The comparison is based on the E_{oed} in the middle of the layer.

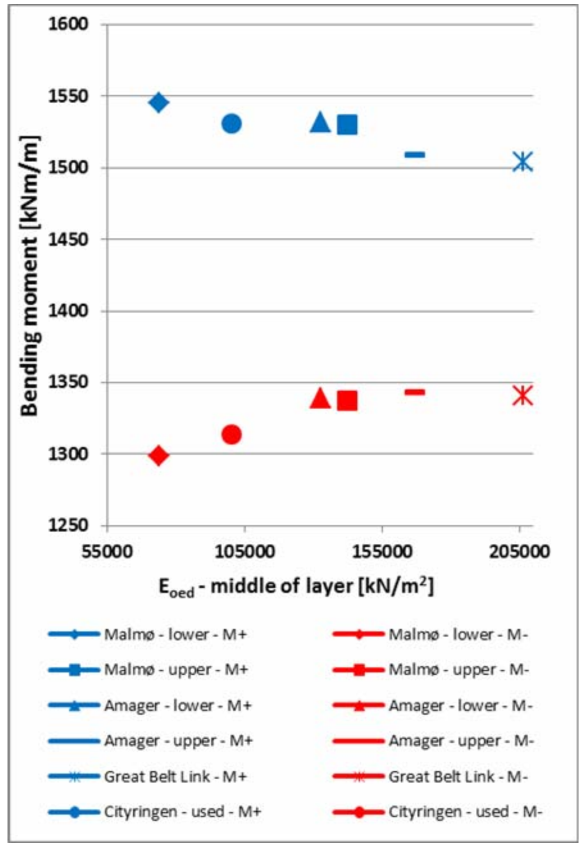

Figure 8.Bending moments from the analysis with different clay till stiffness’

As for the wall stiffness the influence of the clay till stiffness is marginal for the bending moment and anchor forces. Comparing the results for “Malmø – lower” and “Great Belt Link” the increase in E_{oed} in the middle of the layer is 180% but the increase in wall bending moment is only 3% for both the positive bending moment and the negative bending moment of 3%. The upper and lower anchor forces are decreased by 8% and 1% respectively. As verified the stiffness of the soil has only marginal to no influence on the design values.

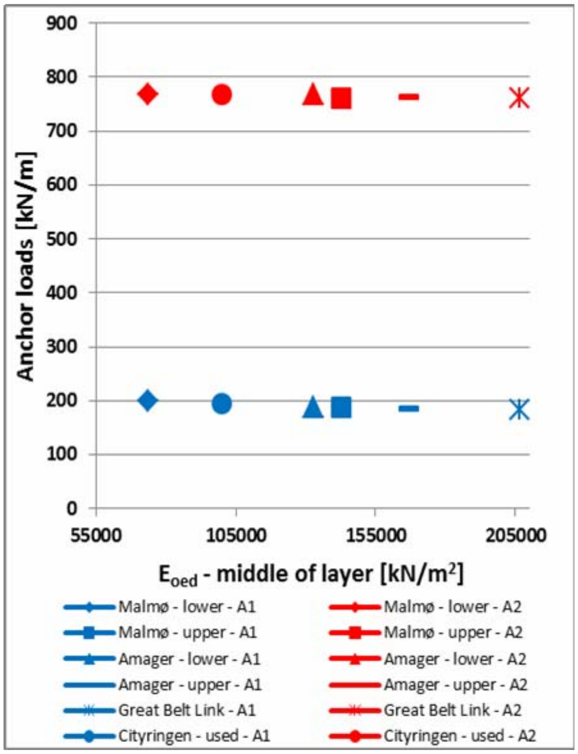

Figure 9.Anchor loads from the analysis with different clay till stiffness'

5.3. Variation of roughness/interaction

The interaction between soil and structure is controlled in PLAXIS by the strength reduction factor, R_{inter}. R_{inter} is connected to the friction angle and adhesion of the soil, but also reduces the interface stiffness. If the R_{inter} is equal to 1 there is full interaction between soil and structure and maximum possible shear stresses along the wall is mobilized. The reduction factor depends on the soil type and structural material. According to (Brinkgreeve, R.B.J., 2015) the value can be assumed to be 2/3 if no further information is given. A similar interaction factor is also used in Denmark when determining the skin friction capacity of piles. For piles in cohesive soil the values is 0.7 for steel piles and 1.0 for concrete piles (Ovesen N.K et. al, 2009).

A roughness factor, *r*, is also used in SPOOKS, which is the ratio between wall friction angle and friction angle of the soil, or ratio between wall adhesion and cohesion in the soil. In SPOOKS the roughness factor has an influence on the bending moment, anchor forces and toe level. In Denmark *r* = 1.0 was normally used until 10-15 years ago, where today *r* is chosen so vertical equilibrium is obtained.

To see if the interaction has any significant influence on the bending moment in a PLAXIS calculation a variation of R_{inter} from 0.5 to 1.0 is carried out. In the project a value of 0.9 has been used, as it is concrete and in general till layers. The results are shown in Figure 10.

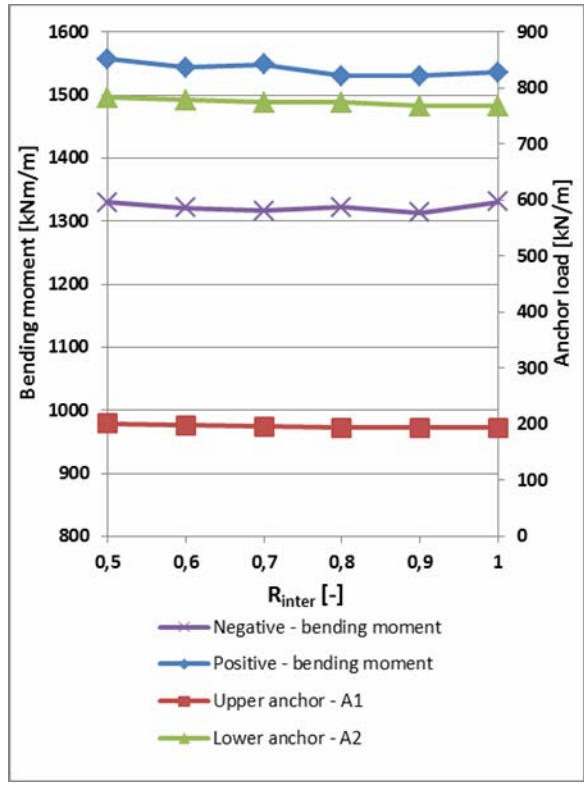

Figure 10.Results of the PLAXIS calculations with variation of the reduction factor, R_{inter}.

The reduction factor does not have any significant influence on the bending moment and anchor forces. The decrease in bending moment is approximately 1% and the anchor forces are 4% and 2% respectively, and as so R_{inter} are of no influence of the design. A similar analysis has been carried out in SPOOKS, where *r* is changed for the clay till. The results are shown in Figure 11, where the results from PLAXIS are included as comparison.

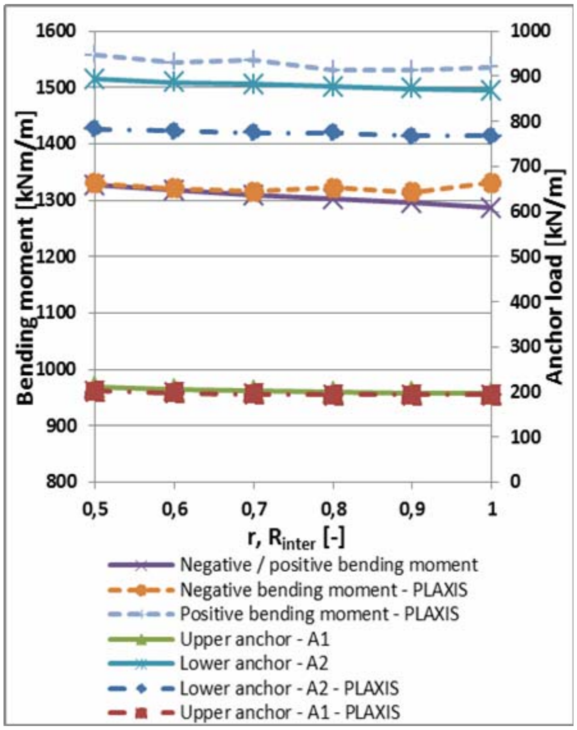

Figure 11.Comparison of SPOOKS and PLAXIS results, when variating *r* and R_{inter}.

The tendency is similar for the SPOOKS calculation as for the PLAXIS calculation. The decrease in bending moment when going from a roughness 0.5 to 1.0 is 3% and 7% for the upper anchor and 3% for the lower anchor.

5.4. Mohr Coulomb vs. Hardening Soil

Due to the stress dependent stiffness behavior of the clay till another soil model that could be feasible to use is the Hardening Soil (HS) or Hardening Soil Small Strain (HS-ST) model. For the design it was assessed that the Mohr Coulomb is sufficient as the surroundings was not sensitive to deformations. Another issue was the amount of inputs that should be determined by assumptions as the needed test for obtaining the correct inputs was not available. To see what influence the choice of soil model has on an ULS calculation a set of HS parameters is determined, as shown in Table 3. The stiffness parameters are determined based on the E^{MC}_{oed} and an assumed *m*-value of 0.8 which is based on experience.

Table 3.Govern hardening soil parameters

	E^{ref}_{ur}	E^{ref}_{50}	E^{ref}_{oed}	m
	[kPa]	*[kPa]*	*[kPa]*	*[-]*
HS	*106E3*	*35E3*	*35E3*	*0.8*

The results of the analysis are shown in Table 4.

Table 4.Results of the MC and HS calculations

	Bending moment - M^-	Bending moment - M^+	Anchor force- A_1	Anchor force - A_2
	[kNm/m]	[kNm/m]	[kN/m]	[kN/m]
MC	-1314	1531	194	768
HS	-1343	1565	212	769

The difference between the two soil models is marginal, which was expected. The increase in negative and positive bending moment, when using HS, is 2.2% and 2.2% respectively. The increase in anchor load is marginally. The results verify that using the simpler Mohr-Coulomb material model is sufficient.

5.5. Variation in pre-stress of anchors

The previous calculations show a difference of approximate 25% for the positive bending moment, which correspond fine with the fact that the lower anchor is approximately 10% lower. In SPOOKS it is not possible to add any pre-stressing to the anchor, but in PLAXIS it is possible to control the anchor force with the pre-stressing force. A normal pre-stress factor used is 0.6 to 0.8 of the ULS anchor load found from SPOOKS. The calculations have been carried out with a pre-stress factor of 0.6 compared to the SPOOKS calculations, which is in the low end. Therefore the pre-stressing is changed in intervals from 0.1 up to 1.0 of the SPOOKS anchor load. The results are shown in Figure 12. As the design load for the upper anchor does not change the result is left out.

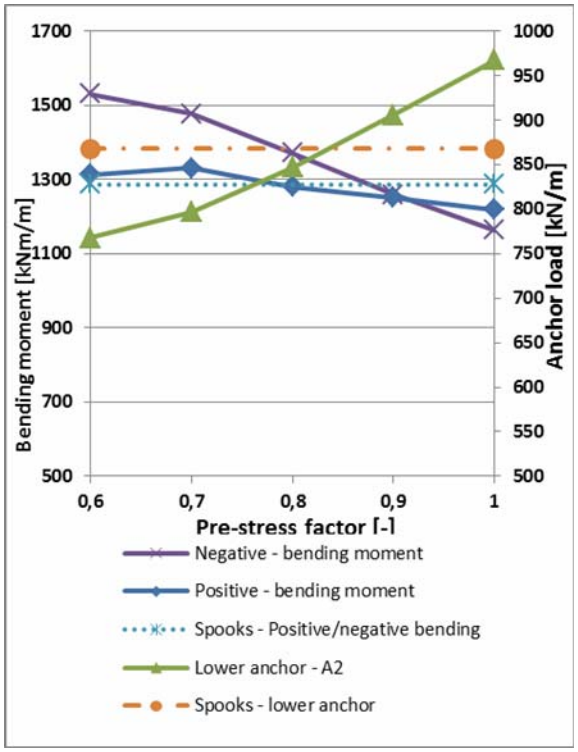

Figure 12.Results of the PLAXIS calculation with pre-stress variation.

In contrary to the other analyzes carried out the pre-stressing shows a significant impact on the bending moment and lower anchors load. The negative and positive bending moment decreases with 7% and 24% respectively. At the same time the lower anchor increases with 26%. That is due to the fact that the anchor takes more loads and thereby decreases the bending moment in the embedded part of the wall. The plot shows that a pre-stress factor between 0.8 and 0.9 (1632 kN – 1835 kN) will give results similar to SPOOKS. As so it is recommended to use a value in that region for the pre-stressing of anchors, if PLAXIS is used for ULS verifications and both positive and negative bending moments are expected in the design.

6. INFLUENCE OF STRENGTH PARAMETERS

To show that the strength parameters have a bigger influence on the bending moment and anchor forces than most of the stiffness inputs investigated in the previous section, 4 calculations with different strength parameters is carried out. The 4 combinations are shown in Table 5 and the results of the calculations are shown in Figure 13.

Table 5.The 4 combinations used for the analysis

Combination	φ' [°]	c' [kPa]
1	30	10
2	30	20
3	34	20
4	34	30

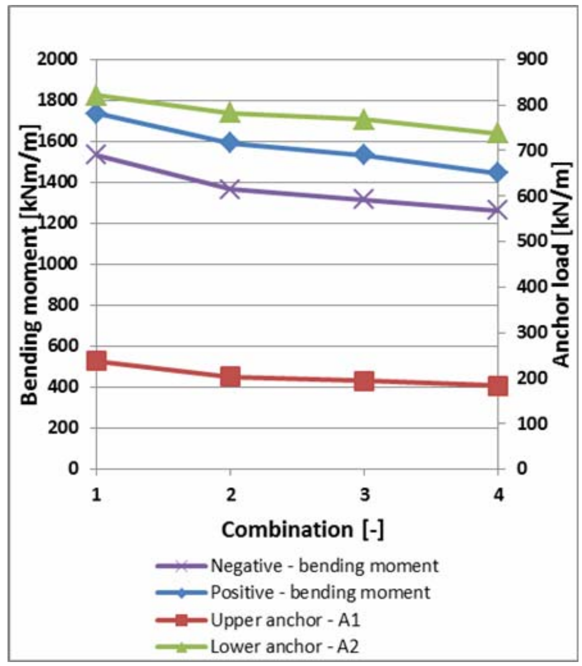

Figure 13.Results of the PLAXIS calculation with variating strength parameters.

The calculations show that small changes in strength parameters decreases the negative and positive bending moment with 18% and 17% respectively. The upper anchor force decreases with 23% and the lower anchor force with 10%. The calculations show that the bending moment and anchor forces are more sensitive to the changes of strength parameters than the stiffness properties of the wall and soil and as so more emphasize should be put on determining correct strength parameters.

7. CONCLUSIONS

From the four different analyses it can be concluded that the stiffness dependent parameters do not influences the section forces and anchor forces, when the soil strati mainly consist of clay till. The increases and decreases are marginally and other inputs like the pre-stressing and strength parameters are assessed to be more decisive for the design, when having retaining walls with 2 anchor layers.

Comparing the Spooks calculation and PLAXIS calculations shows large difference, especially in respect of the positive bending moment and second anchor layer. The difference is due to the pre-stressing force of the second anchor, as shown in section 5.5 an increase of pre-stress factor to a value between 0.8 and 0.9 will give similar bending moment and anchor force.

The calculations show that the results from SPOOKS are reliable and sufficient when designing a retaining wall with 2 anchor layers. The calculations also show that it is more relevant to obtain more precise strength parameters than stiffness parameters deformation is not decisive for the design.

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REFERENCES

Hansen J.B. (1953), "Earth pressure Calculation", Teknisk Forlag, Copenhagen, Denmark

Brinkgreeve, R.B.J., Engin, E., Swolfs, W.M.(2015), PLAXIS 2D version 2015 manual, Delf, the Netherlands,

Ovesen N.K., Fuglsang L.D., Bagge G., Krogsbøll A., Sørensen C.S., Hansen B., Bødker K., Thøgersen L., Galsgaard J., Augustesen A.H, (2009), „Lærebog i Geoteknik", 1st edition, Denmark,

Haarh F., GEO (2008), „SPOOKS/W User's Manual", Denmark