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Design of multi-anchored walls for deep excavations

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ABSTRACT: Multi-propped/anchored walls for supporting deep excavations are widely used in underground construction. Design of multi-propped/anchored walls for deep excavations is a one of the most difficult tasks for geotechnical engineers. It is a complicated soil-structure interaction problem. The presence of, among others, anchor prestress loads makes the problem more complicated. The traditional methods in many cases cannot provide a satisfactory tool for design of multi-propped walls. In this paper, results from FEM analyses of sheet pile walls for deep excavations are discused and compared with the traditional method. The use of the finite element method, as PLAXIS, makes it possible to design the optimal configuration of a multi-propped wall.

1. INTRODUCTION

Design of braced/anchored sheet piles is one of the most complicated soil-structure problems in the geotechnical field. Simplified analytical methods cannot answer complicated design questions. Anchor prestress load is one example. Sheet piling walls are often calculated according to the classic concept of Rankine on active and passive earth pressures. However, with anchor pre-stressing loads, the classic concept of Rankine is no longer correct. Prestress load is used for reducing wall and soil movement. However it is not easy to choose an "optimal" prestress load, which can both reduce displacements and bending moment in the wall as well as shear stress in the dowels. Another problem, the traditional simplified methods often overestimates bending moment in sheet pile walls. In such cases, the design is on the safe side. However, in a certain case the bending moments are underestimated by the traditional methods.

In this paper, some particular deep excavation projects designed by the Author using the finite element method (FEM) with PLAXIS are presented. Through these examples the Author tries to discuss above-mentioned aspects and to illustrate the advantages of FEM-analysis to the traditional methods.

2. PASSIVE EARTH PRESSURE BEHIND THE WALL

Sheet piling walls are often calculated according to traditional simplified methods using for example the classic concept of Rankine on active and passive earth pressures. In this concept the soil behind the wall behaves actively, and the soil at the excavation side behaves passively. However, with anchor pre-stressing loads, the classic concept of Rankine active and passive sides is not longer correct. In reality, the soil at the so-called active side, according to the Rankine concept, just behind a pre-stressed anchor behaves passively.

The first example in this paper is the excavation for Fredriksberg Station in the central of Copenhagen city. The construction of a mini-metro in the city of Copenhagen started in November 1996. The 20.5-km system opened between 2002 and 2007. The metro has 22 stations, of which 9 are underground. In 2009, the metro carried 50 million passengers. Fredriksberg, one of the underground stations, is located at a very dense populated area. The tunnel and station is constructed by Cut & Cover method. The excavation for the project is more than 200m long, 8 to 12m in depth and 25 to 30 m in width.

Figure 1. Overview of the drilled-pile wall at Fredriksberg Station, Copenhagen

In Fig. 1, an overview of the construction site is shown. On the North side, i.e. the right side of the figure, there is a new shopping centre, 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 Client. On the South side of the project is the Old Frederiksberg station that was built in 1864, the oldest railway station in Denmark. It had to be protected during the construction of the Metro. These two existing buildings made the excavation a very difficult and challenging foundation-engineering work, Phung (2001a).

The ground surface level at the studied section is +11.0 m. The soil profile includes the fill layer of 1 m in thickness, the upper clay till layer 6 m thick, the layer of sand/sand till 3 m thick and the lower clay till layer with a thickness of about 7m. The clay till is heavily over-consolidated and has a c_u-value of 150kPa, for the upper layer, and 300kPa, for the lower layer. The limestone is situated at level –6.0m. The modulus of compressibility of the clay till and sand till layers increases with depth and depends on the vertical effective stress. The ground water is situated at level +2.5 m, i.e. 8.5 m below the ground surface. In order to make it easier for comparing the FEM analysis with the traditional Rankine method, the c'-value is ignored for clay till. The soil properties are shown in Table 1.

Table. 1 Soil parameters – Fredriksberg Station, Copenhagen

Soil	Fill	Upper clay till	Sand till	Lower clay till
Y-top, m	+11.0	+10.0	+4.0	+1.0
Model	MC	MC	MC	MC
Mtype	DR	DR	DR	DR
γ-dry, kN/m^3	16	18	18	19
γ-wet, kN/m^3	20	22	22	23
ν'	0.3	0.33	0.3	0.33
E'-layer, MPa	11.1	20.8	88.8	108.7
E'-increase, MPa/m	0.0	15	13.8	15
c' - layer, kPa	1.0	1.0	1.0	1.0
c'- increase, kPa/m	0.0	0.0	0.0	0.0
ϕ' (°)	30	33	38	35

A drilled-pile wall, a quite flexible wall, was used. A pile consists of a steel tube 194-mm in diameter and 6.3 mm thick and a steel HEB-100 core-beam. Every second or third tube is first drilled into the limestone and then filled with the HEB-beam, which is drilled further into the limestone. The space between the tube and the HEB-beam is filled with concrete. The soil between the piles is shotcreted. The pile wall is supported by injected cable anchors of type Supa-lina, with a declination of 30° and spacing between 2 and 4m. For the wall section in study, three anchor levels were used at levels +9.5, +6.0 and +2.5, i.e. at depths -1.5m, -5m and -8.5m under the ground surface.

Both Plaxis and the Rankine method were used for analysing. Using Plaxis, drained analysis is performed. The pile wall is not watertight. The ground water can therefore flow through the pile wall. Two different analyses were done. In the first analysis, a prestress load of 40 kN/m was applied for the upper anchor level and 75kN/m for the two lower anchor levels. In the second analysis the prestress load were 80, 150 kN/m respectively.

The results from Plaxis analysis show clearly that the earth pressure at the so-called "active side" according to the Rankine concept just behind the pre-stressed anchors is much larger than those in the surrounding area. Figure 3 shows that the larger the prestress loads are, the larger earth pressure can be seen. It is obvious that there is a passive zone at the "active" side. In this figure the effective earth pressures obtained from Plaxis analysis is also compared with the results from the Rankine method.

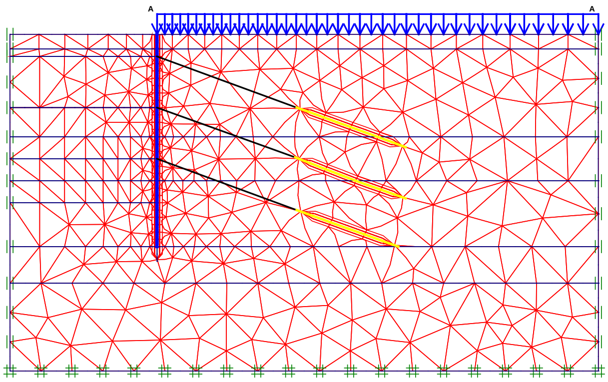

Figure 2. Drilled-pile wall at Fredriksberg Station - Plaxis mesh

3. OPTIMAL ANCHOR PRESTRESS LOADS

Pre-stress anchor loads are often applied for control of the wall movements as well as displacements of the surrounding soil. It is not easy to choose the "optimal" pre-stress loads. In most standards, it is only simply advised that tiebacks are prestressed to about 120 percent of design load and locked off between 75 and 100% of design load. The design load is in its turn calculated from the active earth pressures, according to the classic concept of Rankine active and passive sides. As mentioned above with the presence of anchor pre-stressing loads, the Rankine concept is no longer correct. In reality, the soil at the so-called "active side", behind a pre-stressed anchor will behave passively.

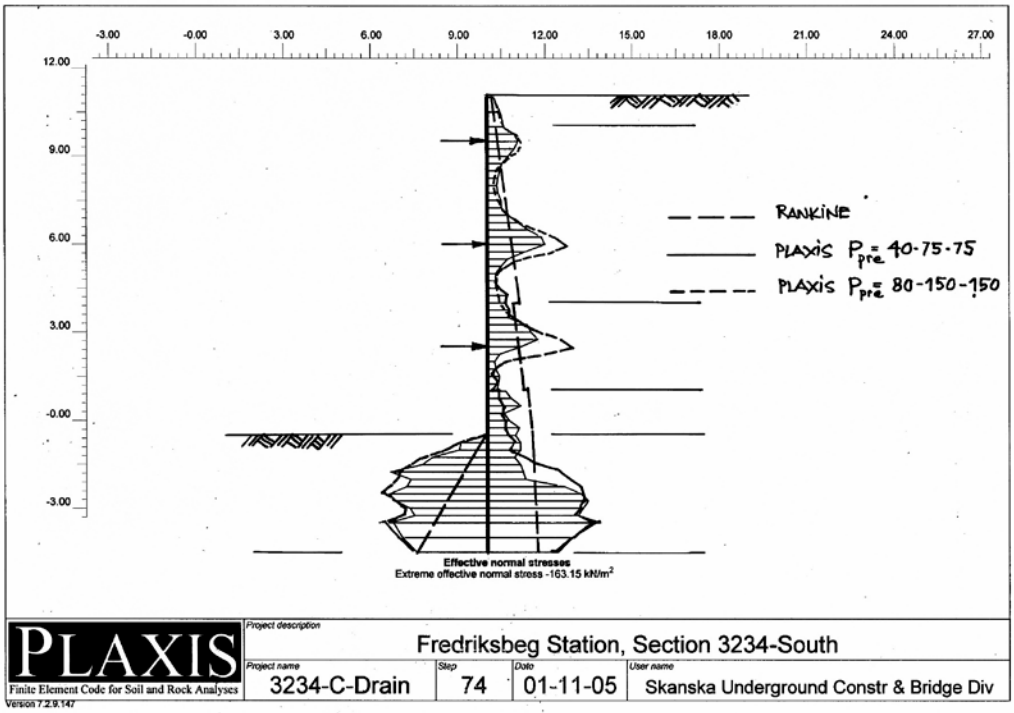

Figure 3. Effective normal stress at wall interface (effective earth pressure)

This also means that larger applied prestress loads may cause larger earth pressure behind the wall. The advice to use a prestress load off between 75 and 100% of design load is perhaps a bit confused.

In the second example in this paper, the sheet-pile wall for the project SL-10, Södra Länken (South Link) in Stockholm, Sweden, is discussed. The link is 6 km in length, of which 4.7 km is in tunnels, Phung (2001b). This makes it the second longest urban motorway tunnel in Europe after Madrid M30 orbital motorway. The construction of Södra länken began in 1997, and was inaugurated in October 2004. The total cost was about 7.9 billion SEK, or 1 billion USD at the 2003-2004 exchange rate. The link was built primarily to decrease traffic in the centre of Stockholm.

The excavation under study is about 400m long, 12-17m deep and 40-50m in width. The section in study is 17m deep. The sheet pile is of LX32 type, driven to the bedrock. Anchors of type Dyform 7∅15.2 mm or 9∅15.2 mm were placed at five different levels +13.5, +10.0, +7.0, +4.0 and +1.0, see Figure 4.The anchors are drilled to the bedrock with an inclination of 45°. Configuration of the sheet pile wall is shown in Fig. 5.

At the studied section, the ground surface level is +15.0m. The soil profile includes a fill layer of 1.5m thick, the upper clay layer 3.5m, and the lower clay layer 12m. The upper clay layer extents to +10m with constant properties. The lower clay layer has undrained shear strength and deformation modulus linearly increasing with depth. Bedrock is found at a level of –2.0m. Soil parameters are summarised in Table 2. The ground water level is +13.5m, i.e. 1.5m below the ground surface.

The staged construction is simulated. The sheet piles are first driven to the bedrock and the first excavation is made to a level of +13.5m, i.e. 1.5 m under the ground surface. The first anchor level is then installed with a pre-stressing load of 200kN/m. The second excavation is made to a level of +10.0 m, i.e. 5 m under the ground surface. Anchors at the second level are then installed with a pre-stressing load of 320kN/m. The process is continued to the final excavation at a level of –2.0m or 17m under the ground surface. During each excavation phase the ground water is lowered to the excavation bottom, which is simulated by a groundwater flow analysis for calculating the new pore water pressure distribution.

Table. 2 Soil parameters – South Link SL10, Stockholm

Soil	Fill	Upper clay	Lower clay
Y-top, m	+15.0	+13.5	+10.0
Model	MC	MC	MC
Mtype	UN	UN	UN
γ-dry, kN/m^3	18.0	17.5	17.5
γ-wet, kN/m^3	21.0	17.5	17.5
ν'	0.3	0.3	0.3
E'-layer, MPa	6.0	4.4	4.4
E'-increase, MPa/m	0.0	0.0	1.4
c' - layer, kPa	1.0	16.0	16.0
c'- increase kPa	0.0	0.0	2.0
ϕ' (°)	35.0	0.0	0.0

A parameter study for seven cases with different pre-stress loads was performed using Plaxis. The case with prestress load 200 kN/m for the first anchor and 320 kN/m for other lower anchors will be used as a reference case, which is called Case 100%. In other cases, prestress loads will be 0%, 25%, 50%, 75%, 125% and 150% of those in the reference 100% case. Let us define the prestress load ratio, PR, as the ratio in percent between the applied prestress load and the reference prestress load, Case 100%. This means that in Case 50% for example, a prestress load of 100 kN/m is applied for the first anchor and 160 kN/m for other anchors.

Figure 4. Overview of sheet pile wall at project SL-10, South Link, Stockholm

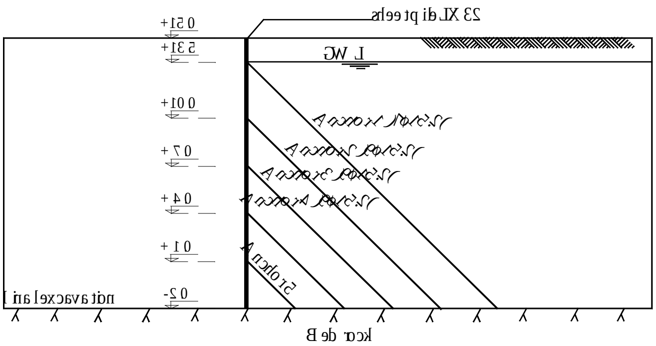

Figure 5. Sheet pile wall at SL10, South Link, Stockholm - Configuration of the problem

In this paper, only the behaviour of the wall at the final stage is studied. The anchor loads at the final construction stage in all cases are drawn versus PR-ratio in Figure 6. It can be seen that even in Case 0%, i.e. no prestress load is applied for any anchor, the final anchor loads are quite comparative with other cases. The final loads in Anchors 1, 2 and 3 have the same tendency, i.e. quite unchanged until PR= 75%, afterward they increase somewhat. The final load in Anchors 5, however, increases almost linearly. The load in Anchor 4 has an intermediate trend.

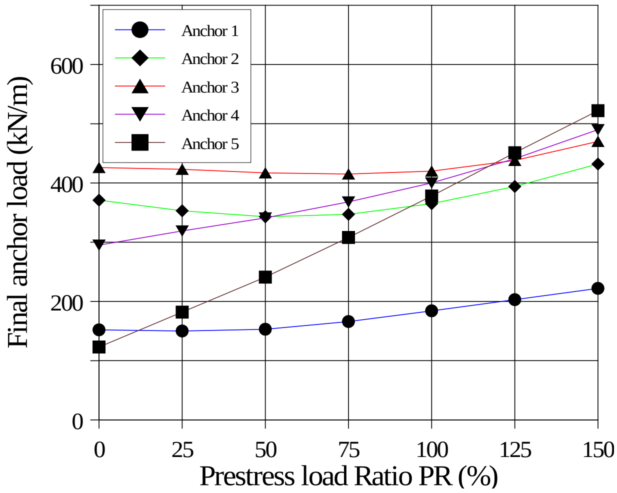

Figure 6. SL-10, South Link, Stockholm - Final anchor loads versus PR-ratio

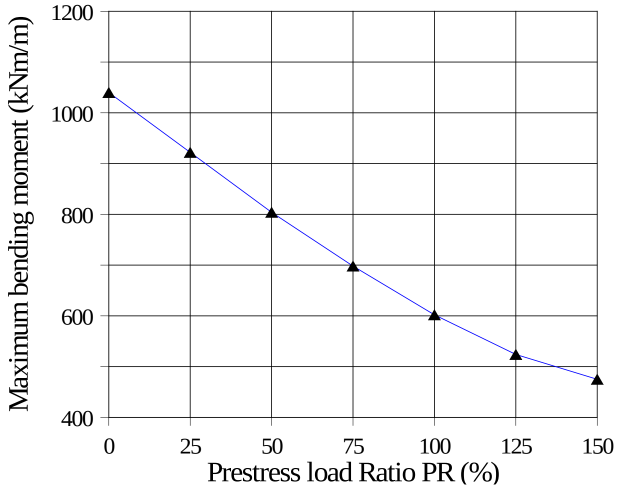

Figure 7. SL-10, South Link, Stockholm - Maximum wall bending moment versus PR-ratio

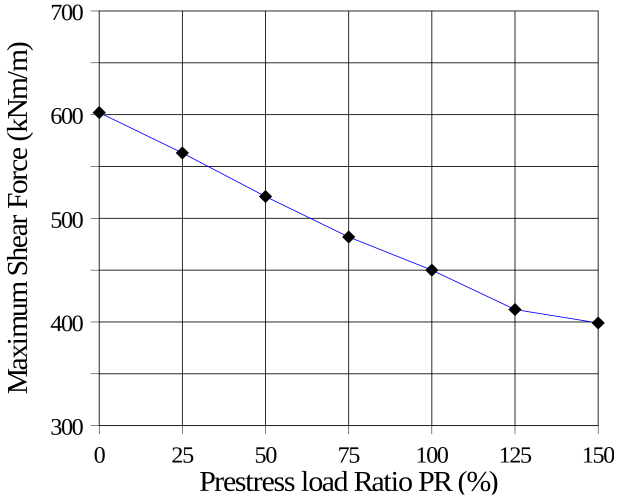

Figure 8. SL-10, South Link, Stockholm - Maximum wall shear force versus PR-ratio

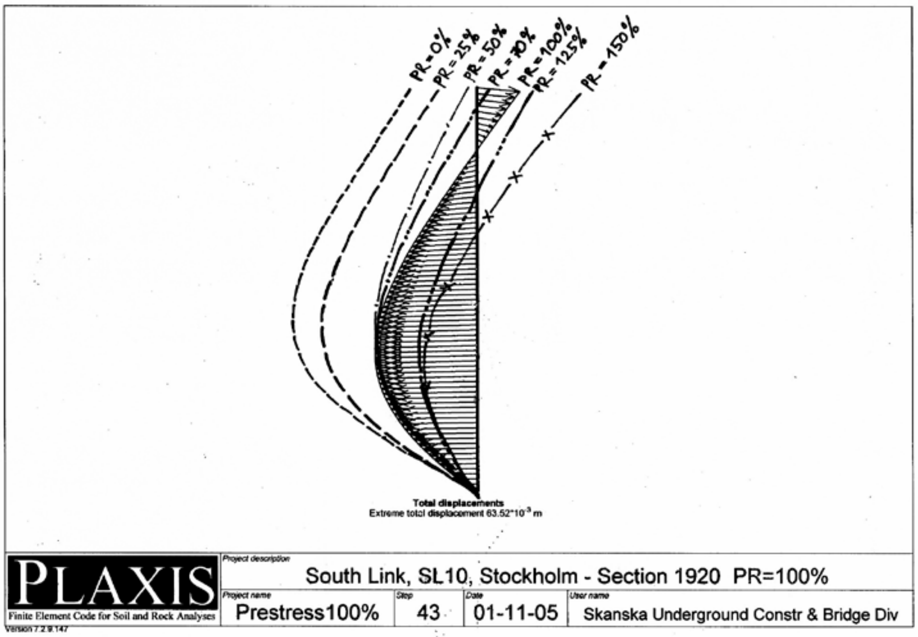

Figure 9. SL-10, South Link, Stockholm - Wall displacement in different studied cases

It can be expected that if a wall have a large number of anchor levels, the final load of all the upper anchors will have the same tendency as Anchors 1, 2, and 3 in this example. This means that no matter how the prestress load is chosen from the beginning, at the final excavation stage the anchor loads will reach to more or less the same value. Choosing correct prestress load can minimise the wall and soil movement, bending moment, as well as shear force in the wall.

With increasing PR ratio, the maximum wall bending moment M_{max} and the maximum wall shear stress Q_{max} decreases considerably, see Figures 7 and 8. This means that the large the prestress load is applied, the lower the bending moment and the shear force in the wall are. The maximum displacement of the wall also decreases considerably with increasing prestress loads, but reaches to a minimum value at PR= 125%, afterward it increases. However at this point PR= 125%, a large backward displacement has happened at the wall top, which may be dangerous for the adjacent existing constructions, see Figure 9.

Which are the "optimal" prestress anchor loads? We can define them as the loads that cause minimum wall movements and at the same time the lowest cost for the wall construction. In this example if considering only bending moment and wall movement, the "optimal" prestress load can be chosen somewhere between PR= 100% and PR= 125%. However with larger prestress load, the anchors and wailing beams need to be stronger and more expensive. Considering this, the "optimal" PR should be chosen between 75% and 100%.

4 BENDING MOMENT IN SHEET PILE WALL

It is well known that bending moments obtained from the traditional analysis is often overestimated for the steel sheet pile walls. Performing a series of model tests on sand of varying relative density, Rowe (1952) showed that wall-soil interaction was different for steel sheet piles and reinforced concrete wall due to the greater flexibility of the steel sheet piles. This greater flexibility causes a redistribution of earth pressure, which differs considerably from the Rankine distribution. These changes reduce the design bending moment for a flexible pile wall.

in Sweden the modified empirical strut load envelope method widely used, Ryner et.al. (1984), the equivalent uniformly distributed pressure $\sigma_i = P_A/(0.9 \cdot H+d)$, where P_A is total active earth pressure up to the balance point, H is excavation depth, and d is distance from the excavation bottom to the balance point.

Figure 10 shows the calculation of earth pressure for the wall at Fredriksberg Station using the above method. In this study case σ_i = 34.5 kPa. If the maximum bending moment in the wall is computed as for continuous spans, $M_{max}= (\sigma_i \cdot h_{max}^2)/10$, where h_{max} is the largest distance between two adjacent anchors, we will have $M_{max}= (34.5 \cdot 3.5^2)/10=$ 42 kNm/m. If M_{max} is computed as for simple span, $M_{max}= (\sigma_i \cdot h_{max}^2)/8= (34.5 \cdot 3.5^2)/8=$ 53 kNm/m. The maximum bending moment obtained from Plaxis analysis in both cases with different prestress loads is approximately 30 kNm/m, which is much lower than M_{max}-values calculated according to the above method.

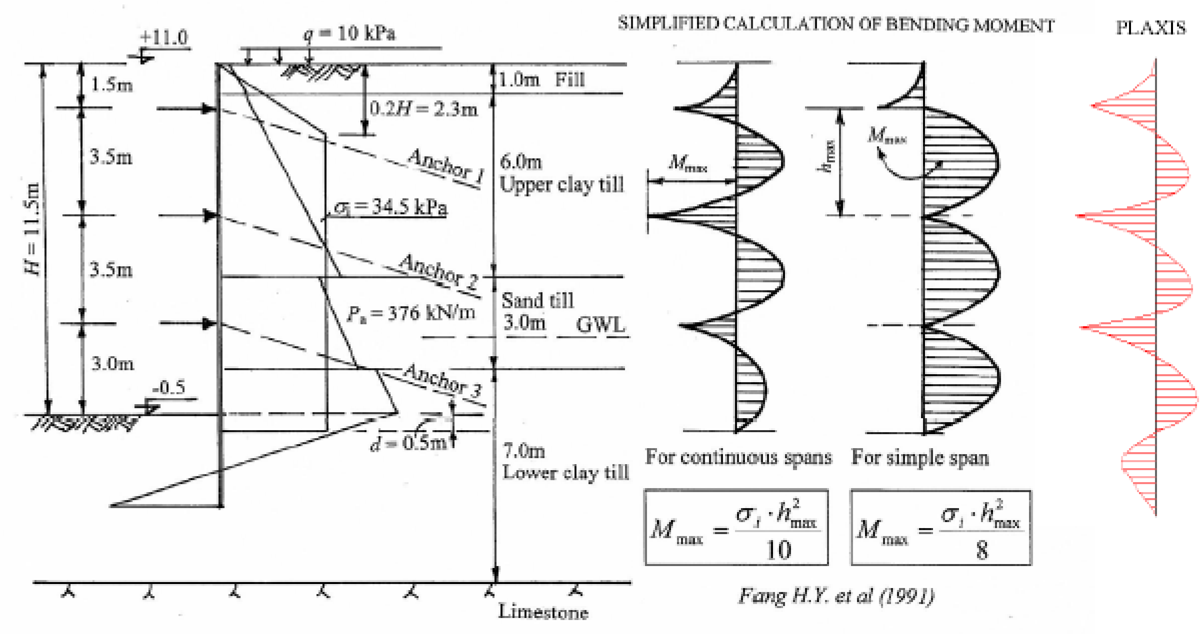

Figure 10. Fredriksberg Station - Calculation of earth pressure and wall bending moment according to traditional method

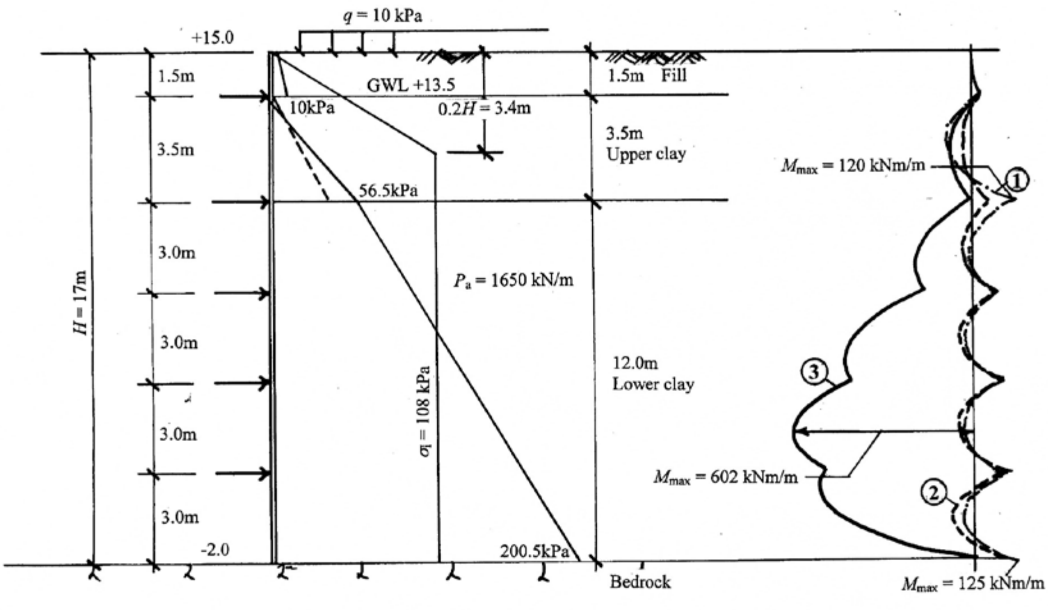

Figure 11. SL-10, South Link, Stockholm - Bending moment calculated according to different methods: 1) continuous spands using σ_i; 2) continuous spands using Rakine earth pressure; 3) FEM method by Plaxis

However, in a certain case, the empirical strut load envelope method can underestimate bending moments. One example is the case where sheet pile wall is driven to bedrock. Let us examine the SL-10 project, South Link in Stockholm. Figure 11 shows the wall bending moment in the final stage for Case 100% obtained from Plaxis, and the maximum bending moment is 602 kNm/m. Using the empirical strut load envelope method the maximum bending moment can be computed as for simple span, $M_{max}= (\sigma_i \cdot M_{max}^2)/8$ or for continuous spans $M_{max}= (\sigma_i \cdot M_{max}^2)/10$. If take $\sigma_i=$ 108kPa from Fig.12, we have $M_{max}=$ 165kNm/m and 132 kNm/m respectively. In Figure 12, the wall bending moments are also calculated by different methods: 1) continuous beam under the equivalent earth pressure estimated according to the empirical strut load envelope method, 2) continuous beam under Rankine active earth pressure, and 3) Plaxis analysis, Case 100%.

The maximum bending moment calculated by the simplified methods are 120 kNm/m and 125 kNm/m respectively, in comparison with the value obtained by Plaxis, 602 kNm/m. It is clearly that the maximum bending moment $M_{\max}$ computed according to the traditional method is much lower than that obtained from Plaxis. This can be explained by the fact that in reality the supports of the equivalent wall-beam are not fixed, while the continuos beam method assumes fixed supports at the anchor levels. We should also recall that the bending moment is a function of the beam displacement $M(x)= E\cdot y^{(2)}$, and the fixities are primarily important. For calculating a sheet pile wall driven to bedrock, other methods than the simple span or continuous spans calculation should be therefore used. In such cases, the frame method, in which anchors are modelled as inclined bars, should be more suitable.

5 CONCLUSIONS

Full analysis of soil and wall stiffness and their interaction using realistic soil constitutive models can be performed by means of FEM method. The principal advantages of such approach include the ability to model wall and soil deformation and stress in a realistic sequence of operation that follow actual construction stages. Prestress anchor load can also be taken into account in a realistic way. By the help of FEM method, some interesting conclusions can be drawn bellow.

For the flexible sheet pile wall with anchor prestress load, the Rankine concept on active and passive side is no longer correct. At the so-called “active” side, just behind the pre-stressed anchors, soil behaves passively.

From the simple parameter study, it can be seen that no matter how the prestress load is chosen from the beginning, at the final excavation stage the load in anchors will reach to more or less the same level. Choosing correctly prestress loads can minimise considerably the wall and soil movement, bending moment, as well as shear force in the wall.

It is well known that bending moments obtained from the traditional analysis is often overestimated for the steel sheet pile walls. However, in a certain case, the traditional simplified method can underestimate bending moment, such as the case of sheet pile wall driven to bedrock. In such cases, as a simplified calculation method, a frame analysis with anchors modelled as inclined bars, may be more realistic.

6 REFERENCES

Fang, H-Y, et al (1991). Foundation Engineering Handbook, McGraw-Hill, N.Y.

Phung Duc Long (2000). Soil stabilisation with lime-cement columns - A solution for deep sheet pile excavations in soft clay". Proc. Int. Conf. GeoEng 2000, Melbourne, Australian.

Phung Duc Long (2001a). Drilled-pile wall for deep excavation at Frederiksberg Station, Copenhagen. Proc. 15th Int. Conf. on Soil Mechanics and Geotechnical Engineering, Istanbul, August, Vol. 2, pp 1147-1150.

Phung Duc Long (2001b). Some aspects in design of multi-anchored walls for deep excavations. The 8th European PLAXIS users meeting, Bundesanstalt für Wasserbau, Karlsruhe, Germany, November.

Phung Duc Long (2004). Why do we need FEM for design of multi-anchored walls for deep excavations? Proc. Vietnamese - Japanese Geotechnical Seminar VJSGE, 27-28 November, Hanoi.

Padfield C.J. and Mair R.J. (1984). Design of retaining walls embedded in stiff clay. CIRIA Report 104, London.

Rowe, P.W. (1952). Anchored sheet pile walls. Proc. Inst. Civ. Engrs, Part 1, Vol. 1, pp. 27-70.

Ryner, A., Fredriksson, A. and Stille, H. (1996). Sheet pile wall handbook. Byggforsknings-rådet, Stockholm. (in Swedish)

Vermeer, P.A. et al. 1998. PLAXIS (Finite Element Code for Soil and Rock Plasticity) Version 7.1 - Users manual. A.A. Balkema, Rotterdam.