

Forensic engineering of a bored pile wall

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Abstract: *At present, bored pile walls in Norway are designed and executed in accordance to regulations of the Norwegian Public Road Administration as described in Handbook R762. During the construction of a 180-meter-long and 18-meter-high bored pile wall for the municipally owned public transporter of Oslo: Sporveien AS, deflections of the wall, the performance of the structural elements and the quality of the welding were monitored on a regular basis. From the evaluation of these data, it was concluded that the geometry of the cross-section did not meet the design requirements. During the construction works, a method was developed to redesign the walls structural characteristics. The performance of materials, products, and structural components used were investigated by forensic engineering. This type of engineering has led to a guideline for future design of bored pile walls. This guideline accounts for:*

- *Design of a bored pile wall with plastic behaviour instead of elastic behaviour;*
- *Calculation of the section modulus in accordance with the achievable structural properties and dimensions;*
- *Design of effective welding with regard to limitations in daily practice;*

It was demonstrated in this case that the bored pile wall still complied with the current design standards and that the guidelines developed may be considered in early design stages with designing and engineering of bored pile walls in future projects.

1 AVLØS STATION

The updating of the Kolsåsbanen includes presence of maintenance and cleaning halls. The intended area however was not big enough and needed to be expanded. In order to widen the area, a large part of an existing slope had to be removed; see the red line in Figure 1 and planned excavation along the retaining wall in Figure 2.



Figure 1 Aerial view of Avløs station,

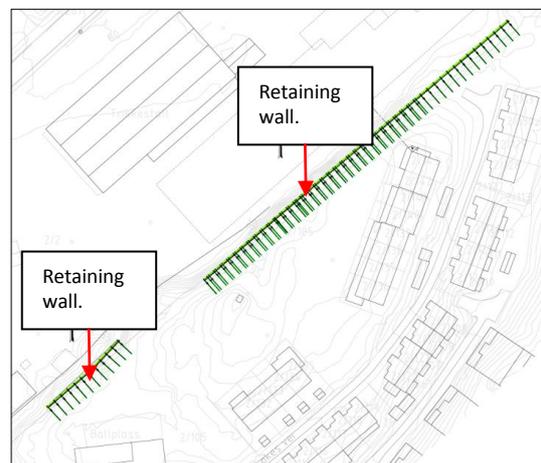


Figure 2 Overview of Avløs station.

1.2 Geological advantages

The geology in the area is a part of the Cambro-Silurian sedimentary rocks of the Oslo region. The sequence consists of limestone, nodular limestone and shale. Figure 3 shows the geological profile.

sectional modulus of the piled wall as well as required dimensions for the anchors were calculated in both the ultimate limit state and the serviceability limit state.

This process resulted in a bored pile wall according to the following drawings and specifications in Figure 7 and Table 1.

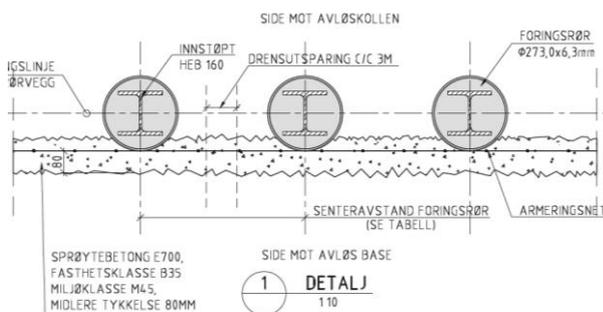


Figure 7 Cross section of the pile wall.

Specifications of bored pile wall at Avløs station		
Total length of bored pile wall	177	m
Maximal height of bored pile wall	18	m
Total number of piles Ø273x6,3	295	pieces
Total length of piles Ø273x6,3	3900	m
Total length of HE160-B piles	3900	m
Total length of braces double UNP350	300	m
Total length of top girdle UNP400	177	m
Total number of anchors	112	pieces
Total length of anchors	735	m
Total cost of materials and installing	16,5 million	NOK

Table 1 Overview of costs and quantities

1.4 Monitoring

In order to achieve the obtained quality, the following steps for monitoring were taken included in the contract:

1. Geometry of the pile wall:
 - Positioning tolerance of the tubular bored pile, +/- 100mm horizontal;

- Placement tolerance of the installed HE160B: rotation of the axis maximum 1% in relation to theoretical axis;
- Control of straightness by measurement with electrical inclinometer;
- Tolerance on HE160B at maximum skewness $D = d:1000$ with $d =$ core diameter;
- Tolerance on cutting of the HE160B at +/- 10mm;
- Tolerance on squareness or perpendicularity of the tubular pipe head: skew $D = d:1000$ with $d =$ core diameter;
- Deviation from theoretical designed level pile top of finished mounted pile top: 50mm;

2. Materials of the pile wall:

- Mortar cement /water factor 0,4 or lower, compressive strength after 28 days: 40 MPa, and further demands from the Norwegian Concrete Association (“Norske Betongforeningen”) publication nr. 14 with necessary tests;
 - Steel grade of the tubular pipes;
 - Material of the HE-B profile;
3. Protocol for each bored pile, including written rapports containing pile number, depth into hard rock, rate of drilling, soil encountered during drilling etc.;
 4. Inspection of welding by both visual inspection and inspection with control with x-ray pictures;
 5. Inspections of the tightness of the welding by controlling the presence of water in the bored pipe;
 6. Inspections of the tightness of the welding by placing water in the pipe, a water lock and to place pressure on the water;

These contractual requirements on quality were carried out in different stages of the process and on a regular basis by control engineers of Sporveien AS with the help of a control plan. The process of installing the bored pile wall had already reached 60% when the control of welding was done by

taking x-ray pictures. The result of these tests showed that up to 60% of all welding work did not meet the requested quality. On top of this, the tests were not sufficient to determine in which degree the welding itself was able to fulfil its duty. The outcome of the test was simply: “approved” or “not-approved”. Besides the fact that the welding was not approved, it showed, during a visit at the building site, that the demand for tolerance on positioning and alignment was exceeded. The image on Figure 8 shows both rotation and translation of the profile beyond acceptable and allowable tolerances. The profiles were displaced with maximum 45 degrees’ rotation in relation to the theoretical axis and in addition against the inner side of the pipe leaving no concrete cover.



Figure 8 Rotated, eccentric and a-symmetric HE-160B profile.

From the evaluation of these data, it was concluded that the quality of the structural cross-section did not meet the design requirements and measures had to be taken.

1.5 Forensic engineering

By contract the tolerance of placement for the HE beams was limited to one-degree rotation. After having spoken with the craftsmen on the job the comment on why the beam had been rotated was: “it will always turn”. There was no further explanation.

The principle is as follows. The straightness of the bored pile depends on the tolerances from both practical side as well as theoretical and contractual side as mentioned before.

Combining these tolerances creates an image as shown in Figure 11 where the bored pile deviates from the theoretical straight line. The different sections, A – D, are sketched in the cross sections below in Figure 9. This Figure shows inconsistency in relation to the theoretical axis.

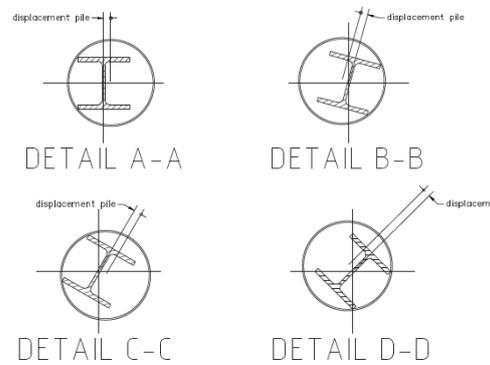


Figure 9 Rotated, eccentric and a-symmetrical profile.

When the HE-B profile is installed, the pile will make contact at one side of the pipe, see Figure 10.

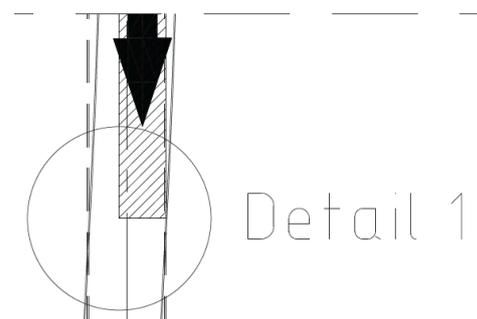


Figure 10 Collision of the profile with the inner side of the pipe.

With this contact the HE-B profile will follow the direction or alignment of the pipe locally which has different directions in cross section A, B, C and D. As a consequence, the HE-B profile will turn and finally rotate.

This process is a direct result of the profiles own weight and therefore the rotational movement goes with great forces which cannot be adjusted during installing neither changed after the profile has reached its final depth.

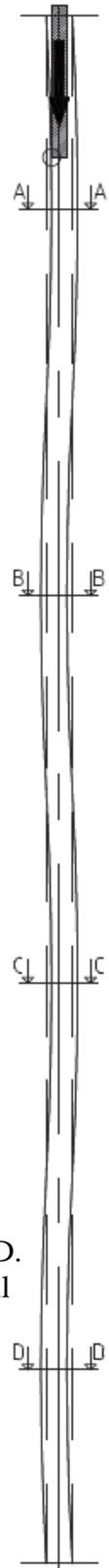


Figure 11: Deviation of practice and theoretical placement.

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After having established the very cause of the rotation and displacement of the combined profile, the next step was to check the influence of this changed combined profile.

See Figure 12 for the calculation of the displaced and rotated profile, with corresponding deviation in relation to the obtained capacity. Table 2 shows an overview.

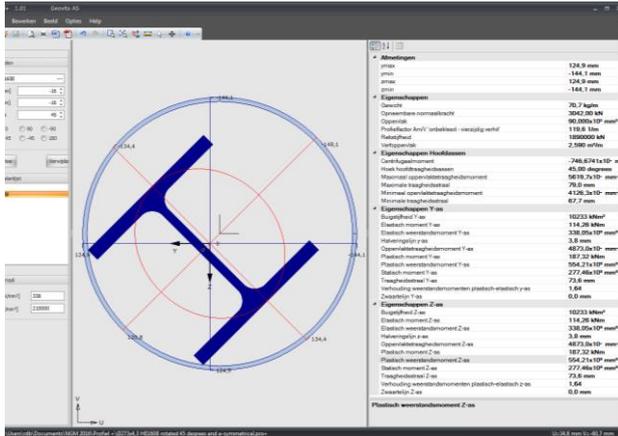


Figure 12 Calculation of the rotated, eccentric and a-symmetric composite profile.

Profile: Ø 269,0 x 4,3 + pored HE160-B	Profil +	Diff. related to centric sym- metric	Profil+	Diff. related to centric, sym- metric
	$M_{y;el;R_d}$ (kNm)	(%)	$M_{y;pl;R_d}$ (kNm)	(%)
Centric and symmetrical	235,37	100	368,98	57
Rotated 15 gr. + symmetrical	230,87	-2	362,18	54
Rotated 30 gr. + symmetrical	218,58	-7	342,27	45
Rotated 45 gr. + symmetrical	201,78	-14	311,15	32
Rotated 45 gr. + a- symmetrical	190,43	-19	312,20	33
Profile: Ø 273,0 x 6,3 corroded with life span 100 years gives Ø 269,0 x 4,3				

Table 2 Capacity overview of the rotated, eccentric and a-symmetric composite pile profile.

It is not allowed to simply add the moment capacity of the tubular pipe and that of the beam, $M_{pipe} + M_{HEB160} = (78,72 + 105) * \text{centre distance} (1/0,6) = 306,4 \text{ (kNm)}$.

This will give considerable more capacity in relation to the calculated. This is due to the fact that both profiles do not have the same neutral line to be followed with calculating the maximum moment capacity, see Figure 13.

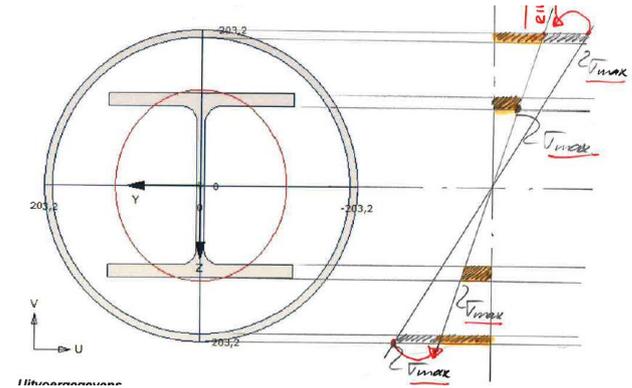


Figure 13 Capacity overview of the rotated, eccentric and a-symmetric composite pile profile.

The capacity of the piles was reduced with 19% in elastic state and approximately 15% for the plastic state. The proper way to calculate the moment of inertia for hybrid profiles with translational and rotational motion is by using Steiner's theorem.

The challenge with the welding was charted by checking welding protocols on welding positions along the tubular pipe. The charted overview visualized that the first elements which were bored, were 6 meters long, containing no welding.

This led to the conclusion that 100% of the designed capacity was still in place over the first 6 meters, of course with deduction of capacity due to corrosion. Along the remaining part of the wall the capacity was reduced to the sum of the rotated profile and the surrounding concrete. Figure 14 shows that calculated data from Figure 12 and Table 2 still provides enough capacity for the lower 6 meters.

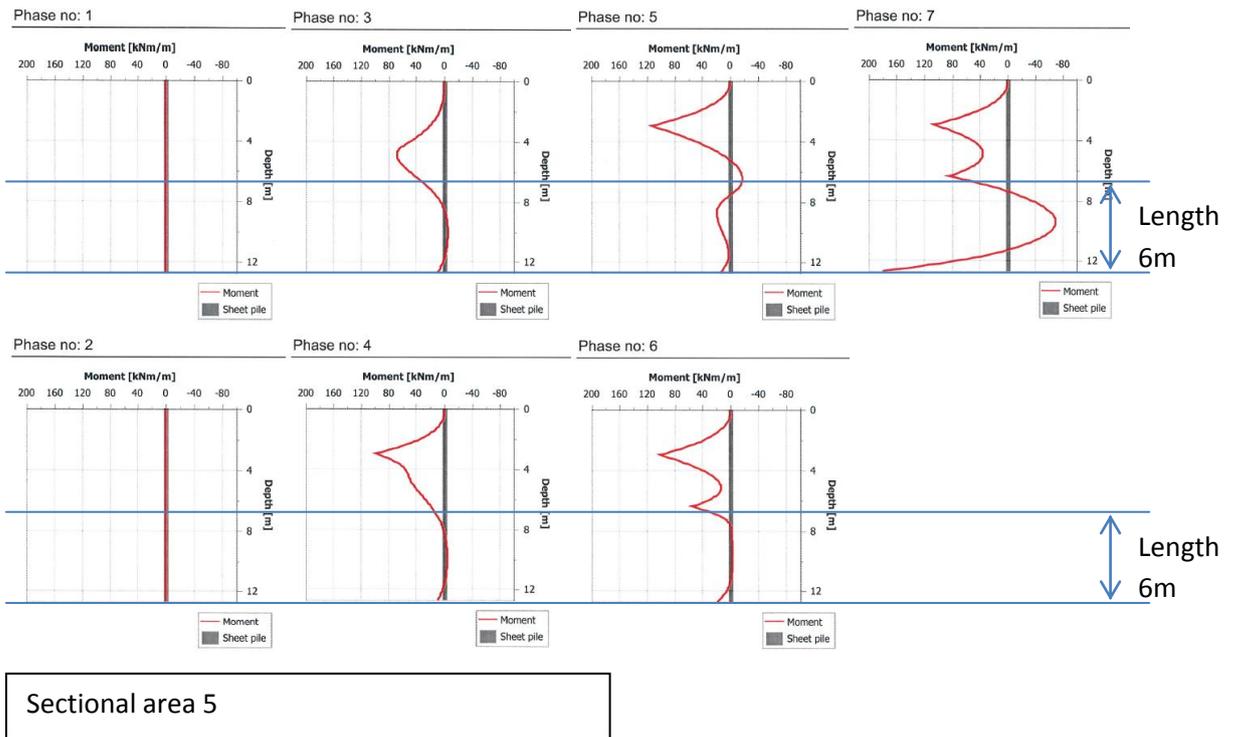


Figure 14 Chartered moment capacities versus placement of welding.

The remaining length was checked by heavily reduced moments of a profile without contribution of the tubular pipe, in addition to capacity calculated as given in the overview of Figure 15 and Table 3. Elastic capacity was reduced with 64% and plastic with 40%.

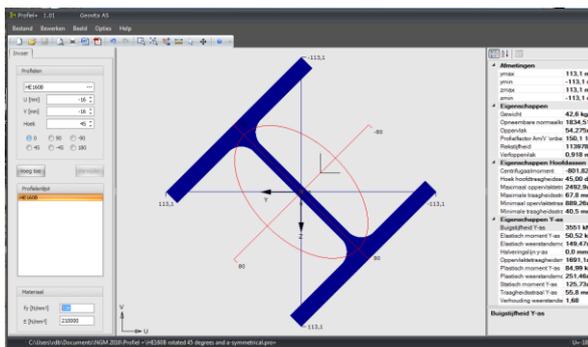


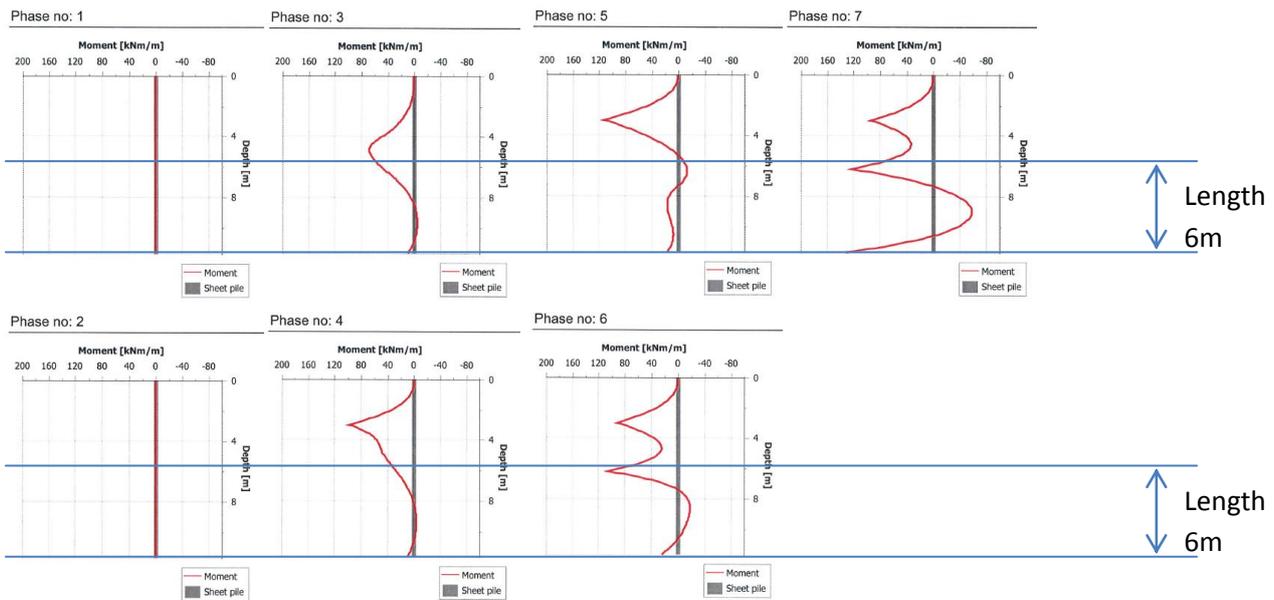
Figure 15 Calculation of the rotated, eccentric and a-symmetrical non-composite profile.

As shown in Table 3 the capacity of these piles was reduced with 64% in elastic state and approximately 40% for the plastic state in relation to the original capacity.

Profile: Ø 269,0 x 4,3 + pored HE160-B	Profil +	Diff. related to centric sym- metric	Profil+	Diff. related to centric, sym- metric
	$M_{y;el:R_d}$ (kNm)	(%)	$M_{y;pl:R_d}$ (kNm)	(%)
Centric and symmetrical	175,55	-25	199,48	-15
Rotated 15 gr. + symmetrical	137,15	-42	192,68	-18
Rotated 30 gr. + symmetrical	107,83	-54	172,77	-27
Rotated 45 gr. + symmetrical	84,20	-64	141,65	-40
Rotated 45 gr. + a- symmetrical	84,20	-64	141,65	-40
Profile: HE160-B with ignored poured concrete shell.				

Table 3 Capacity overview of the rotated, eccentric and a-symmetrical non-composite pile profile.

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Sectional area 5

Figure 16 Chartered moment capacities versus placement of welding.

Other phenomena which need to be checked included:

- Local buckling
- Shear buckling
- Axial – torsional buckling
- Lateral – torsional buckling
- Web crippling and web yielding

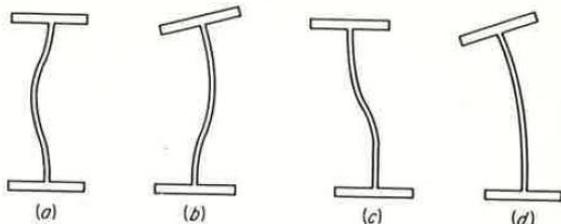


Figure 17 a) Web yielding... d) Web crippling

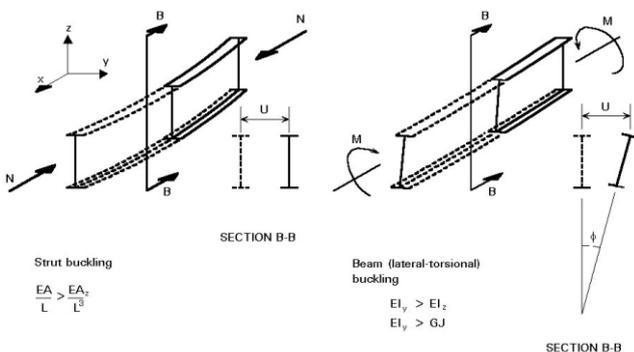


Figure 18 Strut buckling and lateral torsional buckling

The presence of the concrete poured scale surrounding the HE-B profile functioned as plate girder, web stiffener and transverse stiffener which showed to be sufficient after control. The soil anchors with girders functioned as buckling strut, reducing the buckling length considerably.

Controlling capacity after installing showed that in future cases the location of the welding should be done in front. Locations of moment should be linked with necessary welding and described on as-built drawings, preventing welding in the vicinity or directly near locations with large moments in the pile wall. The same is also important for the girders along the pile wall, here it's also possible to end up with welding in the vicinity of or influence zone of large moments. The reduced shear force capacity did not create a problem since this was sufficient from the HE-B profile.

In order to achieve enough covering on the safety a last component was added in the overall control by using the plastic capacity. In order to proceed with this the Eurocode had to be checked whether this way of calculating was permitted.

1.6 CONCLUSION

Monitoring and controlling the bored pile wall showed a considerable amount of inconsistency between design and practice. However solvable the situation turned out, there is a need for improvement of engineering and designing discipline besides the information flow towards contractor in both contract and drawings.

In future projects concerning pile walls it is advisable to take into account the following guidelines:

- A. Calculation of the section modulus in accordance with the achievable structural properties and dimensions. Use of reduced moment capacity as a result of rotated HE-profiles, as a preventive tool;
- B. Design of effective welding with regard to limitations in daily practice.
Homogeneous parts of pipe without welding for the pile wall zones with largest moments. This can also be used as a preventive tool;
- C. Design of a bored pile wall with plastic behaviour instead of elastic behaviour, as a corrective tool in case of deviation from the original design.

2 REFERENCES

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Figure 21 Bored pile wall at Avløs station