Dansk spuns– og rammedag, onsdag d. 10.06.2015

Cross Section – and Member Verification of Steel Sheet Pile Walls According to DS/EN 1993-5

Peter Northved Elf-Lind (M.Sc., Civil Engineer, COWI)

Ole Hededal (Technical Director, COWI)

Agenda

Introduction

Earth pressure theory and deformation requirements

Plastic design model for Class 3 (and 4)

Modifications due to corrosion, water pressures, etc.

Design template and example

Discussions

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Introduction

- Why is this discussion relevant?

- Bridge the understanding of steel designers and geotechnical engineers!

- Acknowledgement: Ole Møller, PAA

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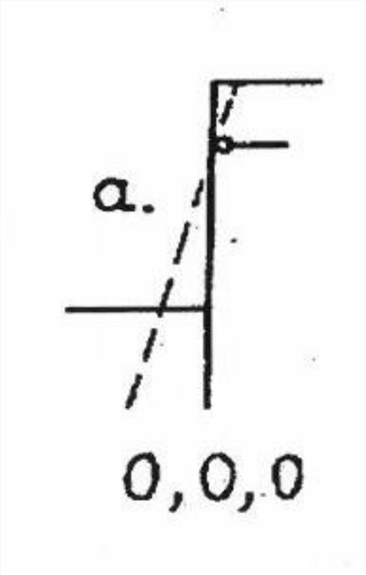
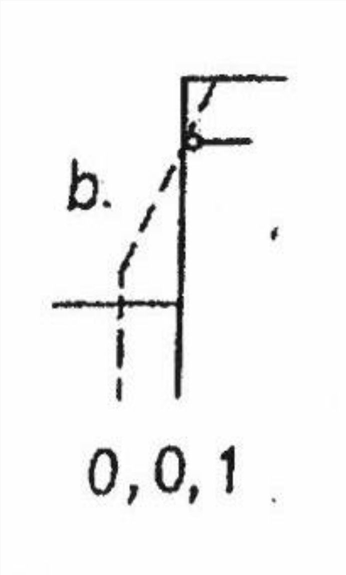
Geotechnical considerations

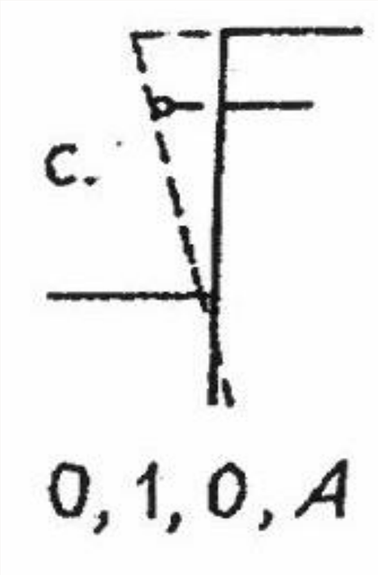
- We need to assure compliance between earth pressure theory and deformation requirements.

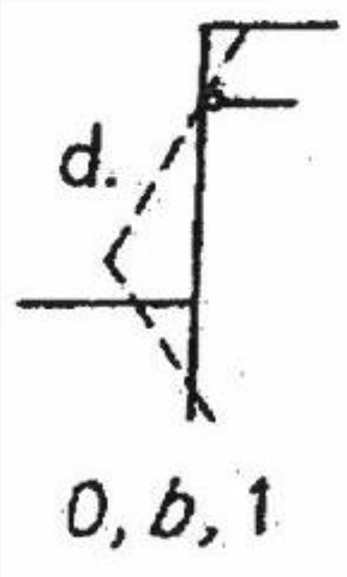
- Is it a problem?
  - No
  - Maybe
  - Yes

Jørgen Brinch Hansen Failure Modes









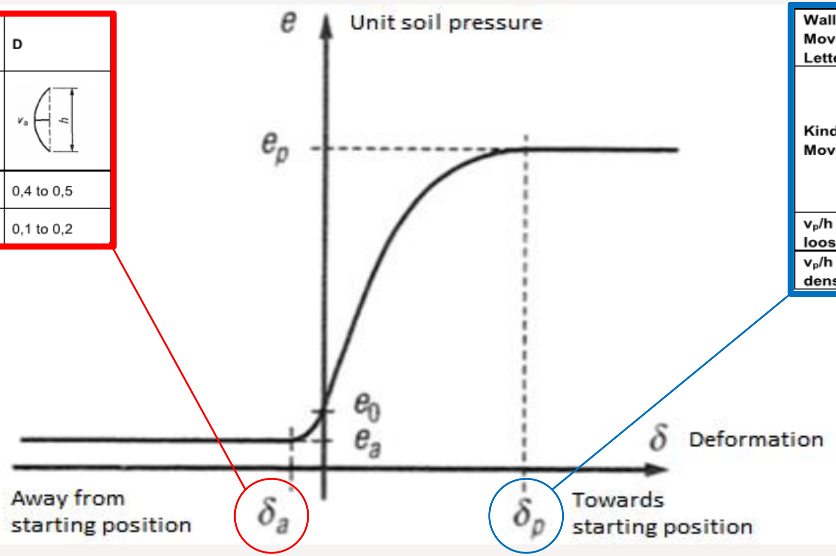
Easy to verify adequate load bearing capacity.

Difficult to verify adequate load bearing capacity due to large rotation.

Mobilization of Plastic Earth Pressures

Wall Movement Letter	A	B	C	D
Kind of Wall Movement	v_a h	v_a h	v_a h	v_a h
v_a/h – ratio, loose soil [%]	0,4 to 0,5	0,2 to 0,3	0,8 to 1,0	0,4 to 0,5
v_a/h – ratio, dense soil [%]	0,1 to 0,2	0,05 to 0,1	0,2 to 0,5	0,1 to 0,2

Conservative ratio magnitudes?



Wall Movement Letter	A	B	C
Kind of Wall Movement	v_p h	v_p h	v_p h
v_p/h – ratio, loose soil [%]	7 (1,5) to 25 (4,0)	5 (0,9) to 10 (1,5)	6 (1,0) to 15 (1,5)
v_p/h – ratio, dense soil [%]	5 (1,1) to 10 (2,0)	3 (0,5) to 6 (1,0)	5 (0,5) to 6 (1,3)

Conservative ratio magnitudes?

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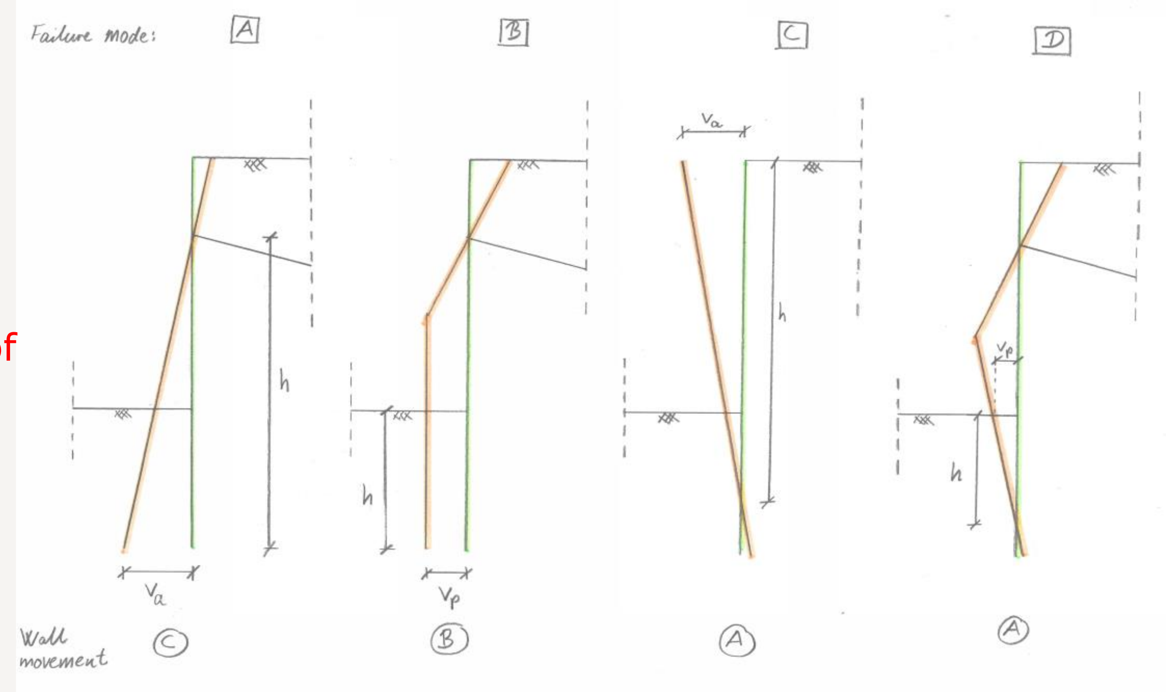
Mobilization of Plastic Earth Pressures – Failure Modes

Simplified/conservative approach to assessment of soil deformations

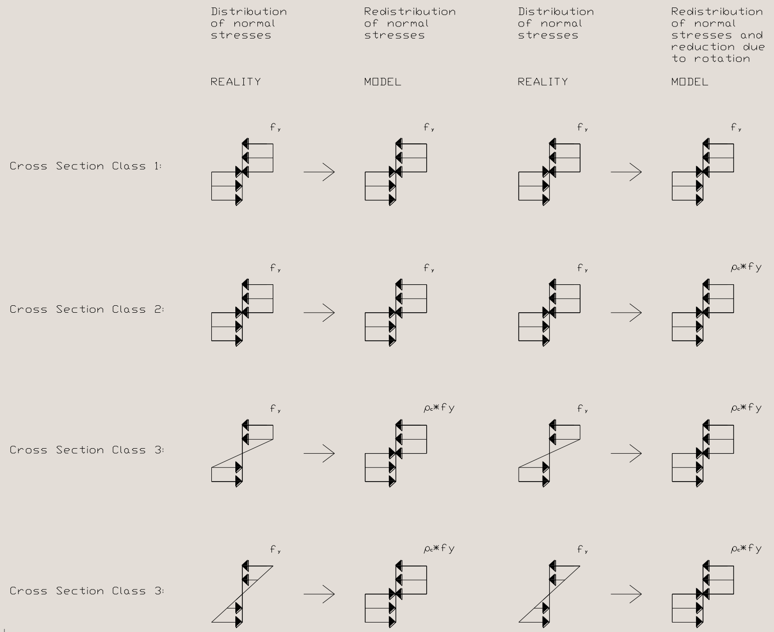


Plastic design model for class 3 (and 4)

- Use of pseudo-plastic design models for Class 1, 2, 3 (and 4)
- Corrections due to corrosion, water pressures, …

Design Principles

Cross sections are considered with plastic normal stress distribution regardless of the cross section class according to the principles shown below:



$M_{pl} \rightarrow$ ok — Rot. cap. $\rightarrow$ ok

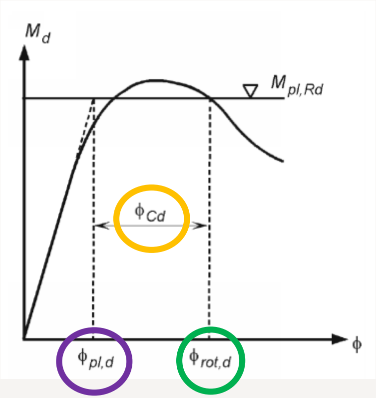
$M_{pl} \rightarrow$ ok — Rot. cap. $\rightarrow \rho_c$

$M_{pl} \rightarrow \rho_c$ — Rot. cap. $\rightarrow \rho_c$

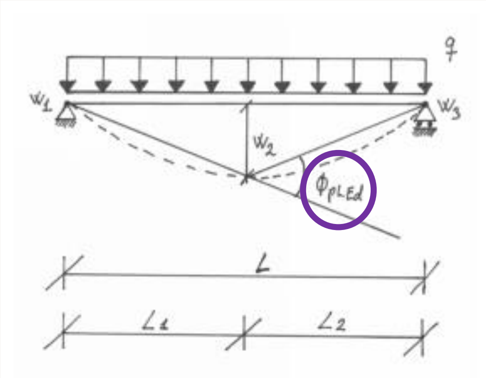
$M_{pl} \rightarrow \rho_c$ — Rot. cap. $\rightarrow \rho_c$

Rotation Capacity

Criteria: $\phi_{Cd} > \phi_{Ed}$



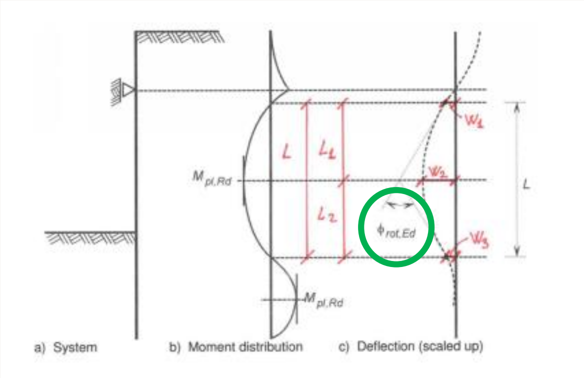
$\phi_{Cd} = \phi_{rot.d} - \phi_{pl.d}$



$$M_{max} = \frac{1}{8} \cdot q \cdot L^2$$

$$w_2 = u_{max} = \frac{5}{384} \frac{q \cdot L^4}{\beta_D \cdot E \cdot I} = \frac{5}{48} \frac{M \cdot L^2}{\beta_D \cdot E \cdot I}$$

$$\phi_{pl.Ed} = \frac{5}{12} \frac{M_{Ed} \cdot L}{\beta_D \cdot E \cdot I}$$

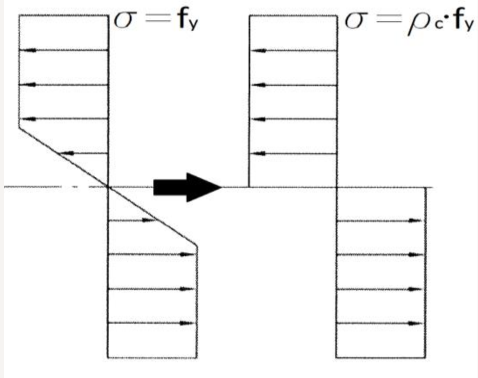


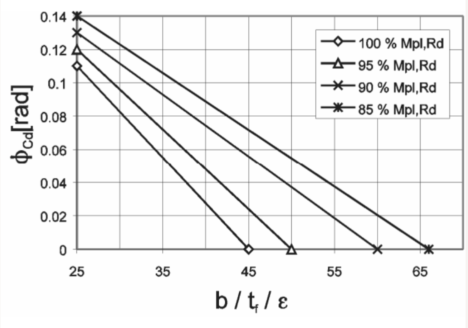
$$\phi_{rot.Ed} = \frac{w_2 - w_1}{L_1} + \frac{w_2 - w_3}{L_2}$$

Residual Bending Moment Capacity

The residual bending moment capacity depends on:

1. The design plastic rotation angle, Φ_{Cd}.
2. The non-dimensional slenderness, $b/t_f/\varepsilon$ (increases due to corrosion).





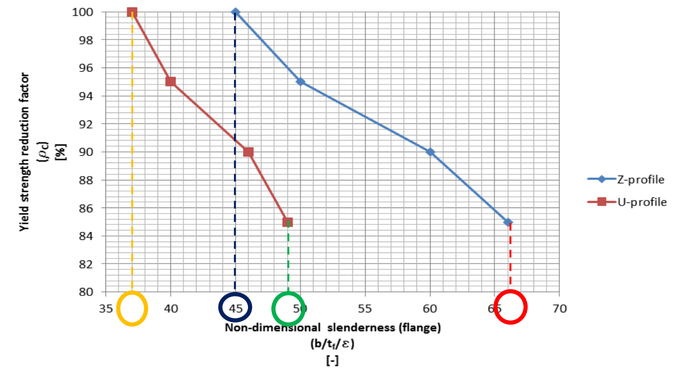
b) Z-piles

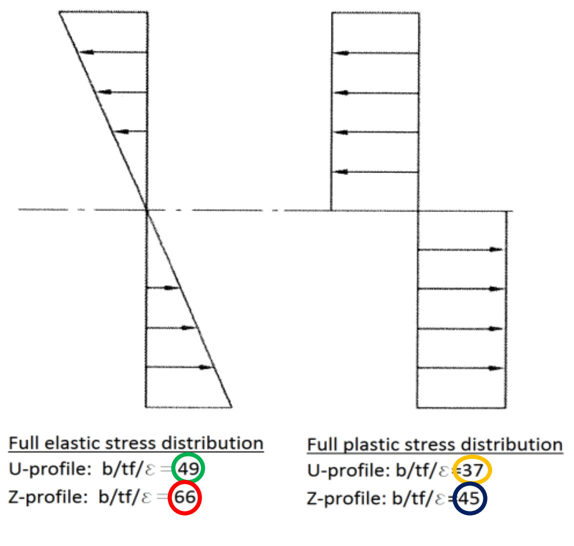
ρ_c = 85% → 85 % Mpl,Rd ~ W_{el}/W_{pl}. If lower residual bending moment capacity, the code does not provide information hereof meaning that profiles assigned to cross section class 4 are omitted.

Residual Bending Moment Capacity - Continued

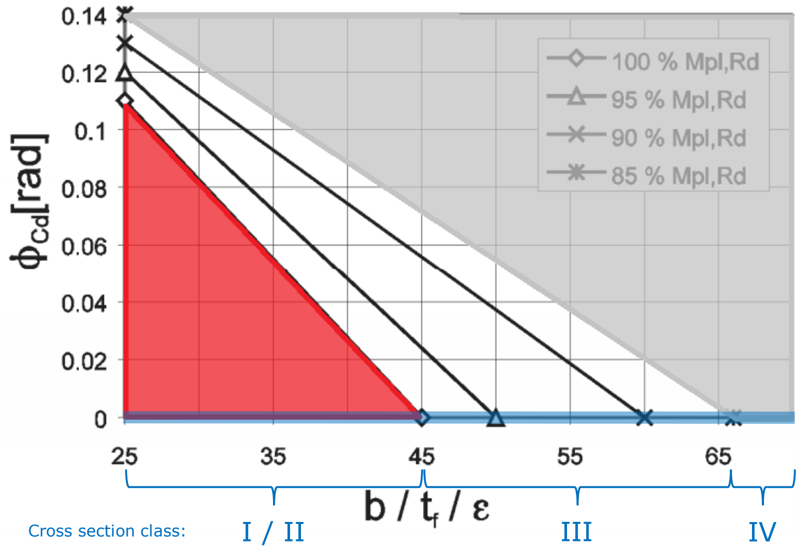
Considering the non-dimensional slenderness, b/tf/ε, only:

Type of pile	M_{plRd}	100 %	95 %	90 %	85 %
	Reduction factor ρ_c	1,0	0,95	0,90	0,85
U-piles	Class 1 or 2	$\frac{b/t_f}{\varepsilon} \le 37$	$\frac{b/t_f}{\varepsilon} \le 40$	$\frac{b/t_f}{\varepsilon} \le 46$	$\frac{b/t_f}{\varepsilon} \le 49$
Z-piles	Class 1 or 2	$\frac{b/t_f}{\varepsilon} \le 45$	$\frac{b/t_f}{\varepsilon} \le 50$	$\frac{b/t_f}{\varepsilon} \le 60$	$\frac{b/t_f}{\varepsilon} \le 66$

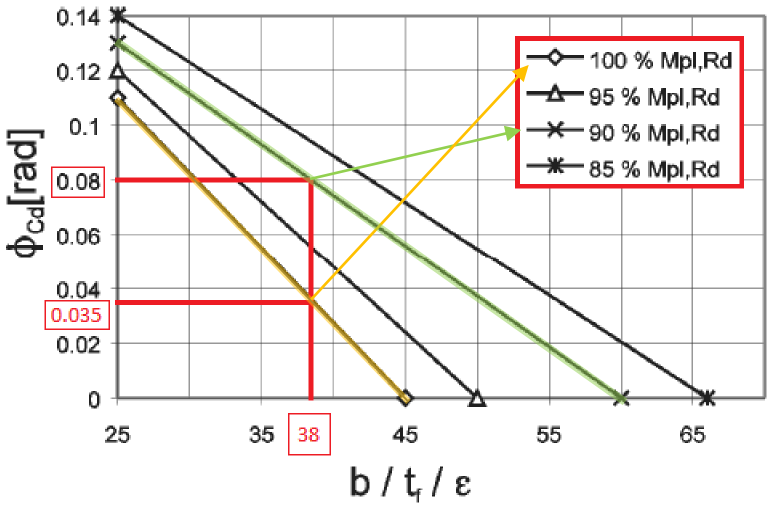




Residual Bending Moment Capacity - Example



b) Z-piles



b) Z-piles

Corrosion Rates

Increase of non-dimensional slenderness due to corrosion impact according to DS/EN 1993-5, Table 4-1 (piles in soils, with or without groundwater – to the left) and Table 4-2 (piles in fresh water or in sea water – to the right):

Required design working life	5 years	25 years	50 years	75 years	100 years
Undisturbed natural soils (sand, silt, clay, schist, ...)	0,00	0,30	0,60	0,90	1,20
Polluted natural soils and industrial sites	0,15	0,75	1,50	2,25	3,00
Aggressive natural soils (swamp, marsh, peat, ...)	0,20	1,00	1,75	2,50	3,25
Non-compacted and non-aggressive fills (clay, schist, sand, silt, ...)	0,18	0,70	1,20	1,70	2,20
Non-compacted and aggressive fills (ashes, slag, ...)	0,50	2,00	3,25	4,50	5,75

Notes:

1) Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills the figures in the table should be divided by two.

2) The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

Required design working life	5 years	25 years	50 years	75 years	100 years
Common fresh water (river, ship canal, ...) in the zone of high attack (water line)	0,15	0,55	0,90	1,15	1,40
Very polluted fresh water (sewage, industrial effluent, ...) in the zone of high attack (water line)	0,30	1,30	2,30	3,30	4,30
Sea water in temperate climate in the zone of high attack (low water and splash zones)	0,55	1,90	3,75	5,60	7,50
Sea water in temperate climate in the zone of permanent immersion or in the intertidal zone	0,25	0,90	1,75	2,60	3,50

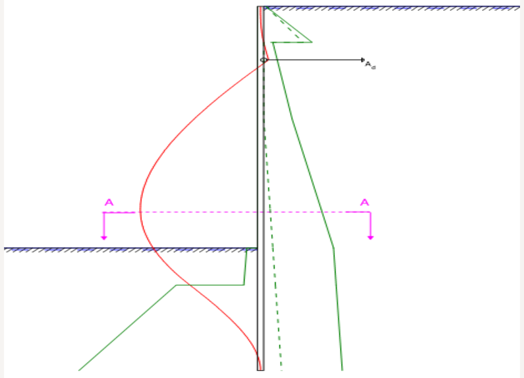
Notes:

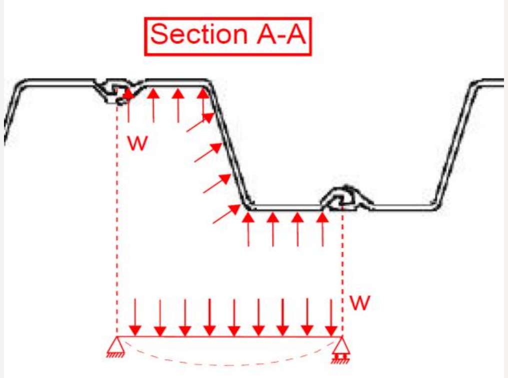
1) The highest corrosion rate is usually found in the splash zone or at the low water level in tidal waters. However, in most cases, the highest bending stresses occur in the permanent immersion zone, see Figure 4-1.

2) The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

Reduction af yield strength due to differential water pressure

- The impact on steel sheet pile wall result in bending about vertical axis (biaxial bending).
- Considered at max. bending.
- Usually, the yield strength reduction factor, $\rho_P \geq 0.95$





›	Z-profiles:	Dif. water pressure > 5 m
›	U-profiles:	Dif. water pressure > 20 m (i.e. practically never)

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Reduction af yield strength due to differential water pressure - Continued

w	$(b/t_{min})\ \varepsilon = 20{,}0$	$(b/t_{min})\ \varepsilon = 30{,}0$	$(b/t_{min})\ \varepsilon = 40{,}0$	$(b/t_{min})\ \varepsilon = 50{,}0$
5,0	1,00	1,00	1,00	1,00
10,0	0,99	0,97	0,95	0,87
15,0	0,98	0,96	0,92	0,76
20,0	0,98	0,94	0,88	0,60

Key:

b is the width of the flange, but b should not be taken as less than $c/\sqrt{2}$, where c is the slant height of the web

t_{min} is the lesser of t_f or t_w

t_f is the flange thickness

t_w is the web thickness

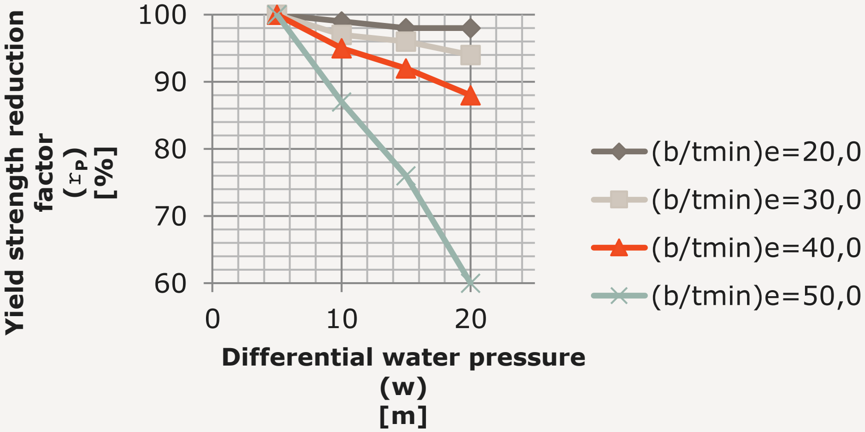
w is the differential head in m

$\varepsilon = \sqrt{\frac{235}{f_y}}$; f_y is the yield strength in N/mm².

Notes:

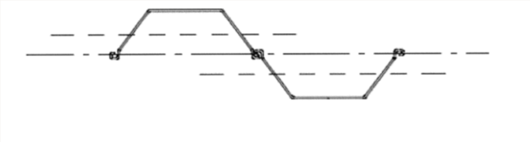
1) $\rho_P = 1{,}0$ may be used if the interlocks of Z-piles are welded.

2) Intermediate values may be interpolated linearly.

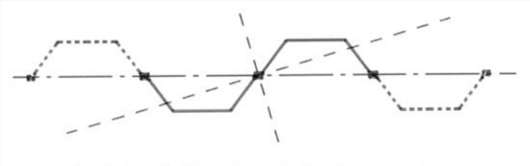


$$f_{y,red} = \rho_P \cdot f_y$$

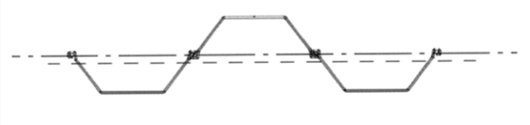
Skew Bending and β - Factors



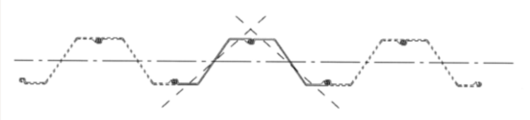
Double U-profile (not crimped or welded together) and major axes



Double U-profile (crimped or welded together) and major axes



Triple U-profiles and major axis



Z-profiles and major axes

$\beta_B = 1{,}0$ for Z-piles and triple U-piles

$\beta_B \leq 1{,}0$ for single and double U-piles.

NOTE 1: The degree of shear force transmission in the interlocks of U-piles is strongly influenced by:

- the type of soil into which the piles have been driven;
- the type of element installed;
- the number of support levels and their way of fixation in the plane of the wall;
- the method of installation;
- the treatment of the interlocks to be threaded on site (lubricated or partly fixed by welding, a capping beam etc.);
- the cantilever height of the wall (e.g. if the wall is cantilevered to a substantial distance above the highest waling or below the lowest waling).

NOTE 2: The numerical values for β_B for single and double U-piles covering these parameters, based on local design experience, may be given in the National Annex.

The β - factors are multiplied to respectively:

- the moment of inertia
- plastic section modulus

Cross Section Analysis (ULS)

The presence of the design plastic rotation angle, Φ_{Cd}, the non-dimensional slenderness, $b/t_f/\varepsilon$, differential water pressure* and skew bending (β - factor) is presented below (here: for bending only):

$$M_{Ed} \leq M_{c,Rd}$$

<u>Class 1 or 2:</u> $M_{c,Rd} = (\rho_C) \cdot \beta_B \cdot W_{pl} \cdot \frac{f_{yk}}{\gamma_{M0}} \cdot \rho_P$

<u>Class 3:</u> $M_{c,Rd} = \rho_C \cdot \beta_B \cdot W_{pl} \cdot \frac{f_{yk}}{\gamma_{M0}} \cdot \rho_P$

*ρ_P is omitted from the formulas in DS/EN 1993-5. Should be multiplied to the expression.

Cross Section Analysis (ULS) - Continued

The mentioned presences only have influence on the bending moment capacity – even at combinations of section forces (here examplified with combined bending moment, shear* – and normal force):

Z-profiles of class 1 and 2:	$\frac{N_{Ed}}{N_{pl,Rd}} \leq 0.1$
U-profiles of class 1 and 2:	$\frac{N_{Ed}}{N_{pl,Rd}} \leq 0.25$
Class 3 profiles:	$\frac{N_{Ed}}{N_{pl,Rd}} \leq 0.1$

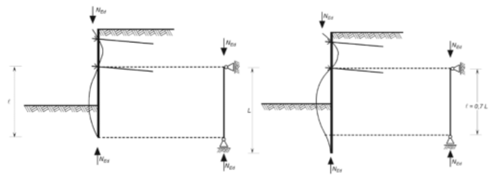
→

Z-profiles of class 1 and 2:	$M_{N,Rd} = 1.11 \cdot M_{c,Rd}\left(1 - \frac{N_{Ed}}{N_{pl,Rd}}\right)$ but $M_{N,Rd} \leq M_{c,Rd}$
U-profiles of class 1 and 2:	$M_{N,Rd} = 1.33 \cdot M_{c,Rd}\left(1 - \frac{N_{Ed}}{N_{pl,Rd}}\right)$ but $M_{N,Rd} \leq M_{c,Rd}$
Class 3 cross sections:	$M_{N,Rd} = M_{c,Rd}\left(1 - \frac{N_{Ed}}{N_{pl,Rd}}\right)$

*It is assumed that the relative shear force utilization does not exceed 50%.

Member Analysis (ULS)

Axial loaded* elements should be studied for column buckling:



Principle behind determination of free column length

If the following criterion is satisfied, the member analysis may be omitted:

$$\frac{N_{Ed}}{N_{cr}} \leq 0.04$$

Otherwise, the following criterion should be satisfied:

$$\frac{N_{Ed}}{\chi \cdot N_{pl,Rd} \cdot \left(\frac{\gamma_{M0}}{\gamma_{M1}}\right)} + 1.15 \frac{M_{Ed}}{M_{c,Rd} \cdot \left(\frac{\gamma_{M0}}{\gamma_{M1}}\right)} \leq 1$$

*For axial loadings, tangential earth pressures are omitted from the sheet pile wall design calculations to simplify the design procedure. Relevant for e.g. bridges vertically supported by sheet pile walls.

TP 50 – semi-automated design procedure

- Use WIN Spooks design program
- Transfer output to Excel-design sheets
- Verification of
  - rotational capacity
  - member capacity based on pseudo-plastic approach
    - reduction of bending capacity from rotation
    - corrosion allowance, differential water pressures
    - reduction for utilisation ratio in normal loading and shear loading
  - global capacity check

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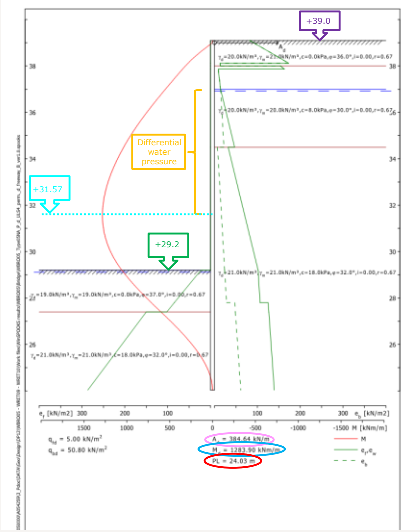
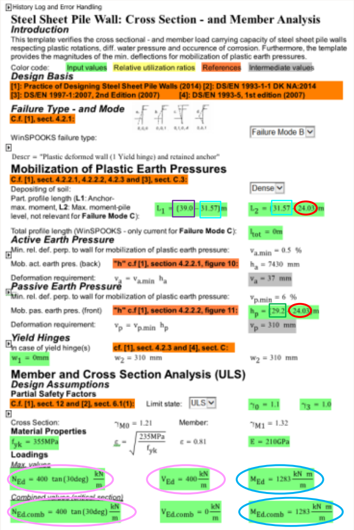
Example – Sheet Pile Wall Analyses (New Approach)




History Log and Error Handling

Steel Sheet Pile Wall: Cross Section - and Member Analysis

Introduction

This template verifies the cross sectional - and member load carrying capacity of steel sheet pile walls respecting plastic rotations, diff. water pressure and occurence of corrosion. Furthermore, the template provides the magnitudes of the min. deflections for mobilization of plastic earth pressures.

Color code: Input values Relative utilization ratios References Intermediate values

Design Basis

[1]: Practice of Designing Steel Sheet Pile Walls (2014) [2]: DS/EN 1993-1-1 DK NA:2014
[3]: DS/EN 1997-1:2007, 2nd Edition (2007) [4]: DS/EN 1993-5, 1st edition (2007)

Failure Type - and Mode

C.f. [1], sect. 4.2.1:

WinSPOOKS failure type: Failure Mode B

Descr = "Plastic deformed wall (1 Yield hinge) and retained anchor"

Mobilization of Plastic Earth Pressures

C.f. [1], sect. 4.2.2.1, 4.2.2.2, 4.2.3 and [3], sect. C.3:

Depositing of soil: Dense

Part. profile length (**L1**: Anchor-max. moment, **L2**: Max. moment-pile level, not relevant for **Failure Mode C**): $L_1 = (39.0 - 31.57)m$ $L_2 = (31.57 - 24.03)m$

Total profile length (WinSPOOKS - only current for **Failure Mode C**): $l_{tot} = 0m$

Active Earth Pressure

Min. rel. def. perp. to wall for mobilization of plastic earth pressure: $v_{a.min} = 0.5\ \%$

Mob. act. earth pres. (back) "h" c.f [1], section 4.2.2.1, figure 10: $h_a = 7430\ mm$

Deformation requirement: $v_a = v_{a.min}\ h_a$ $v_a = 37\ mm$

Passive Earth Pressure

Min. rel. def. perp. to wall for mobilization of plastic earth pressure: $v_{p.min} = 6\ \%$

Mob. pas. earth pres. (front) "h" c.f [1], section 4.2.2.2, figure 11: $h_p = (29.2 - 24.03)m$

Deformation requirement: $v_p = v_{p.min}\ h_p$ $v_p = 310\ mm$

Yield Hinges

In case of yield hinge(s) cf. [1], sect. 4.2.3 and [4], sect. C:

$w_1 = 0mm$ $w_2 = 310\ mm$ $w_2 = 310\ mm$

Member and Cross Section Analysis (ULS)

Design Assumptions

Partial Safety Factors

C.f. [1], sect. 12 and [2], sect. 6.1(1): Limit state: ULS $\gamma_0 = 1.1$ $\gamma_3 = 1.0$

Cross Section: $\gamma_{M0} = 1.21$ Member: $\gamma_{M1} = 1.32$

Material Properties

$f_{yk} = 355MPa$ $\varepsilon = \sqrt{\frac{235MPa}{f_{yk}}}$ $\varepsilon = 0.81$ $E = 210GPa$

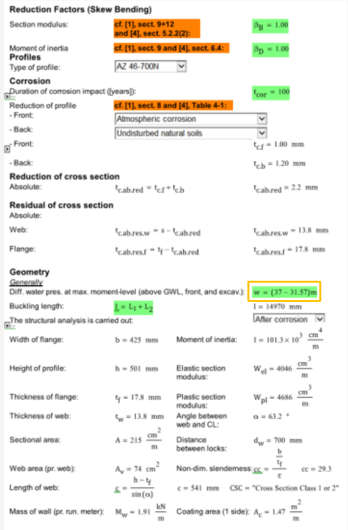
Loadings

Max. values

$N_{Ed} = 400\ \tan(30deg)\ \frac{kN}{m}$ $V_{Ed} = 400\frac{kN}{m}$ $M_{Ed} = 1283\frac{kN\ m}{m}$

Combined values (critical section)

$N_{Ed.comb} = 400\ \tan(30deg)\frac{kN}{m}$ $V_{Ed.comb} = 0\frac{kN}{m}$ $M_{Ed.comb} = 1283\frac{kN\ m}{m}$


Reduction Factors (Skew Bending)

Section modulus: cf. [1], sect. 9+12 and [4], sect. 5.2.2(2): $\beta_B = 1.00$

Moment of inertia cf. [1], sect. 9 and [4], sect. 6.4: $\beta_D = 1.00$

Profiles

Type of profile: AZ 46-700N

Corrosion

Duration of corrosion impact ([years]): $t_{cor} = 100$

Reduction of profile cf. [1], sect. 8 and [4], Table 4-1:
- Front: Atmospheric corrosion
- Back: Undisturbed natural soils
- Front: $t_{c.f} = 1.00\ mm$
- Back: $t_{c.b} = 1.20\ mm$

Reduction of cross section

Absolute: $t_{c.ab.red} = t_{c.f} + t_{c.b}$ $t_{c.ab.red} = 2.2\ mm$

Residual of cross section

Absolute:

Web: $t_{c.ab.res.w} = s - t_{c.ab.red}$ $t_{c.ab.res.w} = 13.8\ mm$

Flange: $t_{c.ab.res.f} = t_f - t_{c.ab.red}$ $t_{c.ab.res.f} = 17.8\ mm$

Geometry

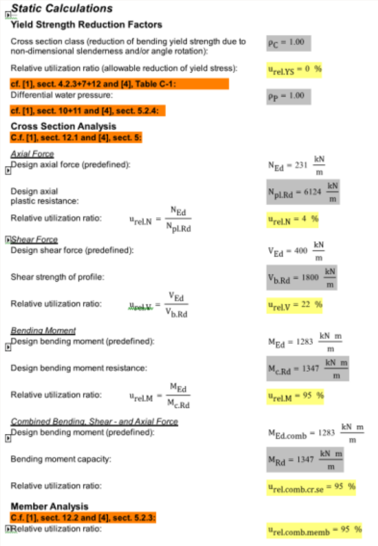
Generally

Diff. water pres. at max. moment-level (above GWL, front, and excav.): $w = (37 - 31.57)m$

Buckling length: $l = L_1 + L_2$ $l = 14970\ mm$

The structural analysis is carried out: After corrosion

Width of flange:	$b = 425\ mm$	Moment of inertia:	$I = 101.3 \times 10^3\ \frac{cm^4}{m}$
Height of profile:	$h = 501\ mm$	Elastic section modulus:	$W_{el} = 4046\ \frac{cm^3}{m}$
Thickness of flange:	$t_f = 17.8\ mm$	Plastic section modulus:	$W_{pl} = 4686\ \frac{cm^3}{m}$
Thickness of web:	$t_w = 13.8\ mm$	Angle between web and CL:	$\alpha = 63.2\ °$
Sectional area:	$A = 215\ \frac{cm^2}{m}$	Distance between locks:	$d_w = 700\ mm$
Web area (pr. web):	$A_v = 74\ cm^2$	Non-dim. slenderness:	$cc = \frac{\frac{b}{t_f}}{\varepsilon}$ $cc = 29.3$
Length of web:	$c = \frac{h - t_f}{\sin(\alpha)}$	$c = 541\ mm$	CSC = "Cross Section Class 1 or 2"
Mass of wall (pr. run. meter):	$M_w = 1.91\ \frac{kN}{m}$	Coating area (1 side):	$A_c = 1.47\ \frac{m^2}{m}$


Static Calculations

Yield Strength Reduction Factors

Cross section class (reduction of bending yield strength due to non-dimensional slenderness and/or angle rotation): $\rho_C = 1.00$

Relative utilization ratio (allowable reduction of yield stress): $u_{rel.YS} = 0\ \%$

cf. [1], sect. 4.2.3+7+12 and [4], Table C-1:

Differential water pressure: $\rho_P = 1.00$

cf. [1], sect. 10+11 and [4], sect. 5.2.4:

Cross Section Analysis

C.f. [1], sect. 12.1 and [4], sect. 5:

Axial Force

Design axial force (predefined): $N_{Ed} = 231\ \frac{kN}{m}$

Design axial plastic resistance: $N_{pl.Rd} = 6124\ \frac{kN}{m}$

Relative utilization ratio: $u_{rel.N} = \frac{N_{Ed}}{N_{pl.Rd}}$ $u_{rel.N} = 4\ \%$

Shear Force

Design shear force (predefined): $V_{Ed} = 400\ \frac{kN}{m}$

Shear strength of profile: $V_{b.Rd} = 1800\ \frac{kN}{m}$

Relative utilization ratio: $u_{rel.V} = \frac{V_{Ed}}{V_{b.Rd}}$ $u_{rel.V} = 22\ \%$

Bending Moment

Design bending moment (predefined): $M_{Ed} = 1283\ \frac{kN\ m}{m}$

Design bending moment resistance: $M_{c.Rd} = 1347\ \frac{kN\ m}{m}$

Relative utilization ratio: $u_{rel.M} = \frac{M_{Ed}}{M_{c.Rd}}$ $u_{rel.M} = 95\ \%$

Combined Bending, Shear - and Axial Force

Design bending moment (predefined): $M_{Ed.comb} = 1283\ \frac{kN\ m}{m}$

Bending moment capacity: $M_{Rd} = 1347\ \frac{kN\ m}{m}$

Relative utilization ratio: $u_{rel.comb.cr.se} = 95\ \%$

Member Analysis

C.f. [1], sect. 12.2 and [4], sect. 5.2.3:

Relative utilization ratio: $u_{rel.comb.memb} = 95\ \%$

Example – Sheet Pile Wall Analyses (Old Approach)

Comparison of "new approach" and "old approach".

Comparison made respecting the flange thickness only. The ratio, r, is obviously larger using the equivalent thicknesses of respectively the web – and flange thickness.

Design Assumptions

Partial Safety Factors

Load combination: $\gamma_0 = 1.1$

Control class: $\gamma_3 = 1.0$

Section forces

Design bending moment: $M_{Sd} = 1284 \frac{kN \cdot m}{m}$

Material Parametres

Steel

Yield strength

- Characteristic value: $f_{y.k} = 355MPa$

- Design value: $f_{y.d} = \frac{f_{y.k}}{1.1 \cdot \gamma_0 \cdot \gamma_3}$ $f_{y.d} = 293MPa$

Geometry

Flange thickness *before* corrosion: $t_{f.before} = 20.0mm$

Corrosion contribution: $t_{cor} = 2.2mm$

Flange thickness *after* corrosion: $t_{f.after} = t_{f.before} - t_{cor}$ $t_{f.after} = 17.8mm$

Section Modulus

"Old Approach"

Required section modulus: $W_{req.old} = \frac{\frac{M_{Sd}}{f_{y.d}}}{\frac{t_{f.after}}{t_{f.before}}}$ $W_{req.old} = 4917 \frac{cm^3}{m}$

"New Approach"

Utilization ratio: $u_{rel} = 95\%$

Selected section modulus (plastic, after corrosion): $W_{pl} = 4686 \frac{cm^3}{m}$

Required section modulus: $W_{req.new} = u_{rel} \cdot W_{pl}$ $W_{req.new} = 4452 \frac{cm^3}{m}$

Comparison Between Approaches

Ratio: $r = \frac{W_{req.old}}{W_{req.new}}$ $r = 110\%$

Conclusions

- Semi-automated design procedure is implemented successfully

- Plastic design of class 3 profiles can lead to savings compared to elastic design model.
- Soil deformations may be evaluated by simplified/conservative approaches based on Eurocode 7 recommendations.
- Especially for projects where the selection of profile is governed by installation or other design drivers, the longterm capacity may be documented even for corroded sheet piles.

Next steps

- Do we dare to use class 4 members?
  - a consultant's point of view
  - a contractor's point of view
- Corrosion - a show stopper?
- Will this work for softer deposits where ULS is the main design driver?