VERIFICATION OF ADEQUATE ROTATION CAPACITY FOR STEEL SHEET PILE PROFILES BY LEM WALL CALCULATIONS WITH YIELD HINGES

O. Møller

KEYWORDS

Limit Equilibrium Method (LEM), ductility, failure modes, mobilisation of plastic earth pressures, yield hinges, steel sheet piles, rotation capacity ϕ_{Cd}, necessary rotation ϕ_{Ed}, cross section classes, link between steel (EC3-5) and geotechnical design (EC7-3).

ABSTRACT

Where LEM wall calculations involve yield hinges (by plastic global analysis), adequate rotation capacity of the sheet pile cross section shall be verified. The paper highlights the interface between EC3-5 and EC7-3 regarding way and background for verification of adequate rotation capacity of sheet pile profiles even for cross section Class 3 by guidance to determination of the rotation capacity ϕ_{Cd} and the necessary rotation ϕ_{Ed} beyond the elastic rotation of the cross section. A calculation example is provided.

1. INTRODUCTION

Since the early fifties designing of retaining walls in Denmark has been based on plastic earth pressures calculated according to the earth pressure theory developed by J. Brinch-Hansen. The earth pressure is redistributed according to the failure mechanism including none, one or more yield hinges and/or involving relieving (yielding) supports like anchors. Plastic design is more cost effective (requires less material) than elastic design. At that time most sheet pile profiles were quite compact and of a moderate steel strength, i.e. ductile, so nobody cared about rotation capacity of the sheet pile profiles. Since then, the sheet pile manufacturers have developed wider and thinner sections with higher steel strength to utilise the weight of the steel optimally. However, this has created the need for verification of the adequate rotation capacity of sheet pile profiles used for retaining walls based on calculation models with yield hinges. This paper provides guidance of such verification with reference to the new EN 1993-5 Design of steel structures – Part 5: Piling (EC3-5) and EN 1997-3 Geotechnical design – Part 3: Geotechnical structures (EC7-3).

2. LIMIT EQUILIBRIUM METHOD (LEM)

By limit equilibrium methods for retaining structures (constant) plastic earth pressures are assumed on both the retained and excavated side. The length (embedment) of the wall is increased until moment and force equilibrium are achieved. The method does not give any information of the displacement of the retaining structure. It is just presupposed that the displacement is adequate to mobilise the plastic earth pressures.

Failure mechanisms

To mobilise plastic earth pressures a failure mechanism must be anticipated. Safety factors applied either directly on the calculated earth pressures or indirectly on the soil strength parameters provide the necessary safety against the anticipated failure mechanism.

Some but not all failure mechanisms cause an earth pressure redistribution compared to a triangular pressure distribution, and some but not all failure mechanisms require yielding of the wall or the anchorage. All mechanisms can be composed by a rotation and/or a translation of the wall. Some typical examples of failure mechanisms are shown in the Figure 1 below.

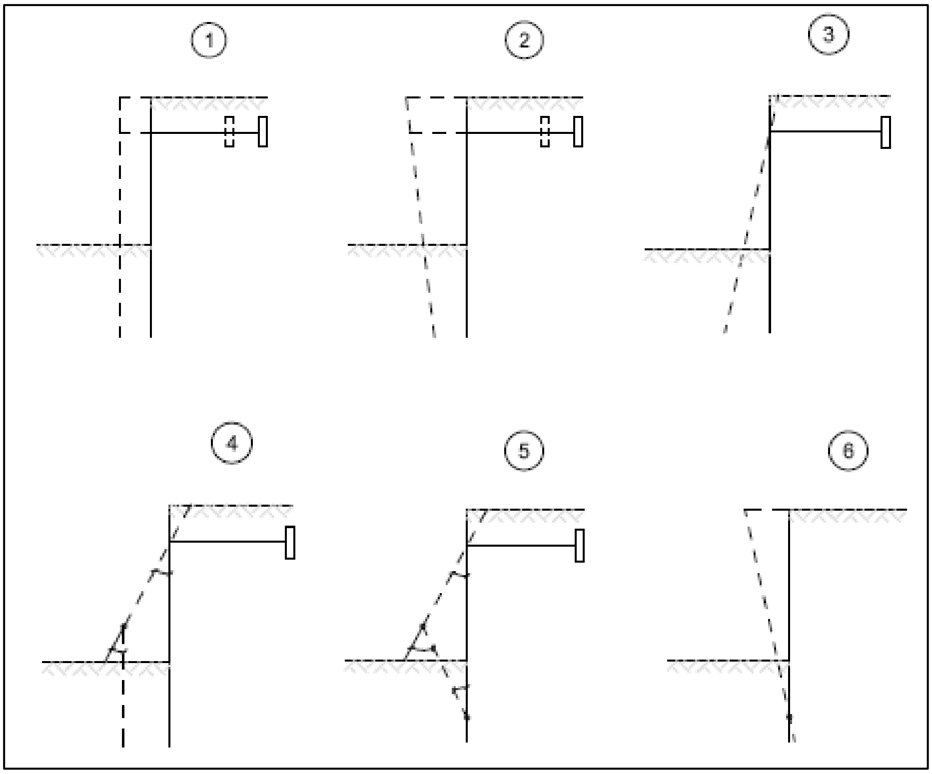


Figure 1 Failure mechanisms

In mechanism 1 and 2 the anchor is yielding, by yielding of the steel tendon or by translation of the anchor plate, the dead man (anchor) mobilising passive earth pressure on the front side of the dead man.

In mechanism 3 and 6 the wall is rotating like a rigid body around a fixed point, in mechanism 3 around the fixed anchor point, in mechanism 6 around the fixation point in the ground.

In mechanism 4 and 5 the upper part of the wall is rotating about a fixed anchorage point, and the lower part of the wall is translating in 4 and rotating about a fixation point in the ground in 5.

Only mechanism 4 and 5 involves a yield hinge in the wall.

Mobilisation of plastic earth pressures

The limiting criteria for mobilisation of plastic earth pressures appear from EC7-3, Annex D.8 Limit equilibrium models, paragraph (2) and corresponding note:

(2) When limit equilibrium models are used to justify plastic hinges in metallic structures accordingly with EN 1993-5, limit displacements associated with limit earth pressures may be estimated based on conventional order of magnitude, traditionally expressed as a proportion λ_a of the wall height on the retained side, and λ_p of the embedded depth on the excavated side.

NOTE   The values of λ_a and λ_p are 0,1 to 0,3 % and 1 to 5 % respectively, unless different values are given in the National Annex.

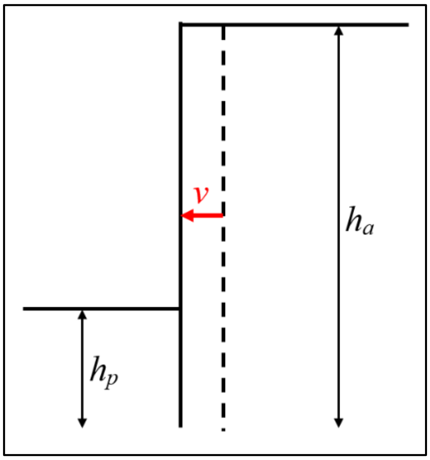


Figure 2 Mobilisation of plastic earth pressures

$\lambda_a = \nu / h_a$

$\lambda_p = \nu / h_p$

$\nu = \max(\nu_a ; \nu_p)$ to mobilise active as well as passive plastic earth pressure

Assume $\lambda_p \sim 10\ \lambda_a$.

Then ν_p is most critical, if $h_p > 0{,}1\ h_a$ which is very typical.

Index a for active and p for passive pressure/side.

3. ELASTIC OR PLASTIC GLOBAL ANALYSIS

Methods of analysis considering material non-linearities (of steel) appear from Cl. 7.4 in EC3-5 as well as EC3-1-1 (same clause number).

Quote from EC3-5, 7.4:

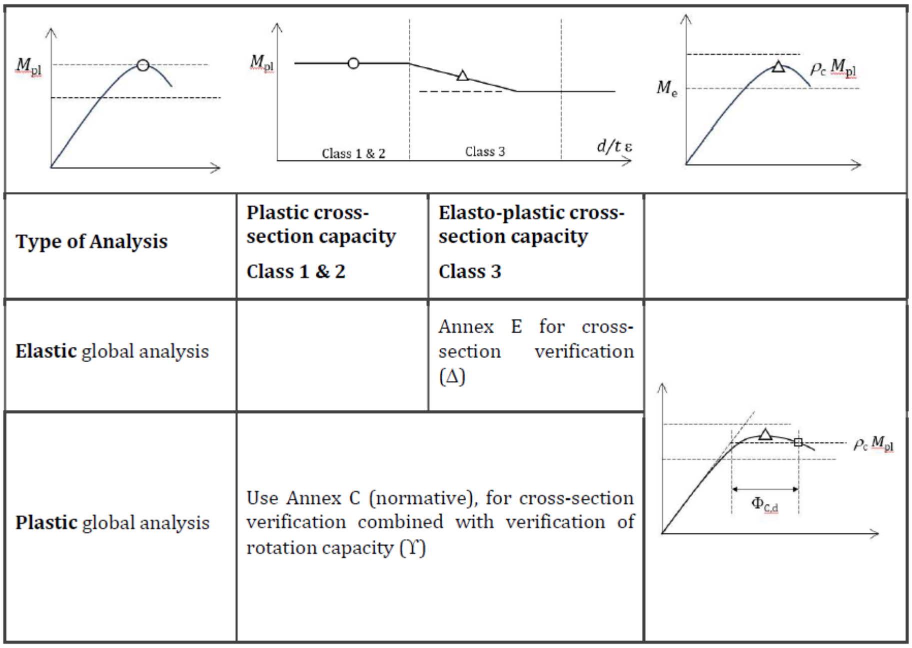
(1) The internal forces and moments may be determined in accordance with EN 1993-1-1, using either

a) elastic global analysis or

b) plastic global analysis.

(2) For elasto-plastic cross-section verification of Class 3 sections, in combination with elastic global analysis, use Annex E (normative), according to Table 7.1

(3) To replace EN 1993-1-1:2022, 7.4.1(3) for U and Z sheet piles, a plastic global analysis may be used in accordance with Annex C for structures made of steel grades up to S460. For other cross-sections EN 1993-1-1:2022, 7.4.1(3) applies.



Type of Analysis	Plastic cross-section capacity Class 1 & 2	Elasto-plastic cross-section capacity Class 3	
Elastic global analysis		Annex E for cross-section verification (Δ)	
Plastic global analysis	Use Annex C (normative), for cross-section verification combined with verification of rotation capacity (ϒ)		

Figure 3 Resistance in bending according to the type of analysis (draft Table 7.1 from FprEN 1993-5)

Normally you would consider and calculate a cross section as plastic being Class 2 OR as elastic being Class 3. However, EC3-5 Cl. 7.4 allows for utilization of the semi-plastic capacity of Class 3 cross sections.

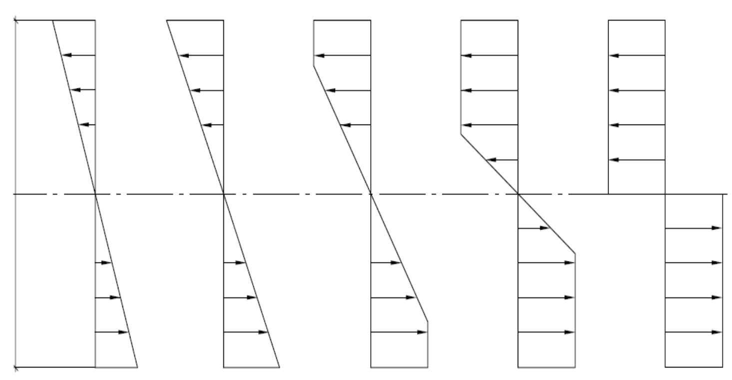
In EC3-5 Table 7.1 it is misleading that “Class 1” is mentioned at all. You can turn a Class 2 section into a Class 1 section, provided you can document that the cross section has the adequate rotation capacity, but you do not know that until you have determined the necessary rotation capacity from the wall calculation, i.e. the necessary λ_a and λ_p. and by this v_a and v_p. On the other hand, even if you manage to document adequate rotation capacity for a Class 3 cross section you would not term that a Class 1 cross section ... by “jumbing” over the Class 2 term. Hopefully / probably the term “Class 1” will disappear from Table 7.1 in the final version of EC3-5 for Formal Vote.

This paper deals with documentation of the adequate rotation capacity using plastic global analysis in accordance with EC3-5 Annex C for Class 2 and Class 3 sheet pile cross sections.

4. CROSS-SECTION CLASSES

The cross-section classes are described in EC3-1-1, 7.5.2 (1). Table 1 below illustrates the stress distribution and degree of plasticity depending on the cross-section class.

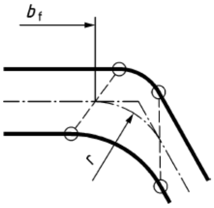
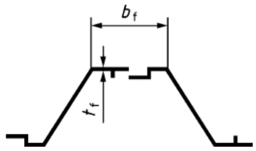
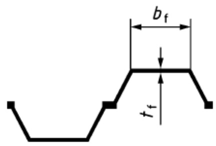
Table 1 Stress distribution depending on cross section class

Stress distribution					
Edge stress	$\sigma < f_y$	$\sigma = f_y$	$\sigma = f_y$	$\sigma = f_y$	$\sigma = f_y$
Class	4	3			2
Type	elastic	elastic	elasto-plastic		plastic

Class 3 sections cover all stress distributions from pure elastic up to pure plastic. Class 2 covers only one stress distribution: the full plastic.

To quantify the limits between Class 2, 3 and 4, a kind of relative slenderness ratio $\lambda = b_t / t_f / \varepsilon$ is defined, where b_f and t_f is the width and the thickness of the flanges, and ε is a weighting factor taking the yield strength f_y

into consideration. The higher yield strength the higher relative slenderness ratio. The limits appear from EC3-5, Table 7.2 which is inserted as Figure below.

Classification	**Z-profile**	**U-profile**
		
Class 1	— the same boundaries as for Class 2 apply — a rotation check shall be carried out according to Annex C	
Class 2	$\frac{b_f/t_f}{\varepsilon} \leq 35$	$\frac{b_f/t_f}{\varepsilon} \leq 35$
Class 3	$\frac{b_f/t_f}{\varepsilon} \leq 60$	$\frac{b_f/t_f}{\varepsilon} \leq 49$

$\varepsilon = \sqrt{\frac{235}{f_y}}$	f_y [N/mm²]	240	270	320	355	390	430	460
	ε	0,99	0,93	0,86	0,81	0,78	0,74	0,71

Figure 4 Classification of cross-sections for U- and Z-profiles (Table 7.2 from EC3-5)

It is not clear why b_f is determined in such a sophisticated way. Using the inner straight part of the flange width, which is listed in every (or most) sheet pile catalogues seem precise enough. The free software Durability from ArcelorMittal renders the value of b_f. The error of using the inner straight part of the flange width is insignificant, e.g. for AZ20-800 b_f is 436 mm whereas the inner straight part is 428 mm. Assuming f_y = 240 MPa, b_f = 436 mm means $b_f/t_f/\varepsilon$ = 46,4 ~ 46. With b = 428 mm $b_f/t_f/\varepsilon$ = 45,5 ~ 46.

5. ROTATION CAPACITY

The design rotation capacity ϕ_{Cd} is defined as the rotation capacity of the cross section beyond the elastic limit as appear from Figure C.2 in EC3-5, pasted below.

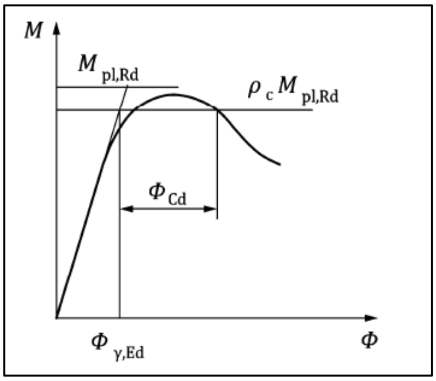


Figure 5 Definition of the rotation capacity angle ϕ_{Cd} (Figure C.2 from EC3-5)

ϕ_{Cd} depends on the utilisation or reduction of the plastic bending resistance $M_{pl,Rd}$ defined by the reduction factor ρ_c, which ranges from 1,00 (full plastic) to 0,85 (pure elastic). Comparison between the elastic modulus W_{el} and the plastic modulus W_{pl} will for most sheet pile profiles be close to 0,85.

The elastic rotation $\phi_{elastic}$ is assumed linear up to the elastic limit $\phi_{y,Ed}$ corresponding to the reduced plastic moment resistance ρ_c $M_{pl,Rd}$, which is an approximation.

The residual bending moment resistance of a cross-section may be determined by using relative slenderness ratios b_f / t_f / ε according to table C.1 in EC3-5, pasted below.

Table 2 Reduction of bending moment resistance $M_{pl,Rd}$ (Table C.1 from EC3-5)

Reduction factor ρ_c on $M_{pl,Rd}$	1,00	0,95	0,90	0,85
Class	2	3		
U-piles	$\frac{b_f/t_f}{\varepsilon} \leq 35$	$\frac{b_f/t_f}{\varepsilon} \leq 40$	$\frac{b_f/t_f}{\varepsilon} \leq 44$	$\frac{b_f/t_f}{\varepsilon} \leq 49$
Z-piles	$\frac{b_f/t_f}{\varepsilon} \leq 35$	$\frac{b_f/t_f}{\varepsilon} \leq 43$	$\frac{b_f/t_f}{\varepsilon} \leq 52$	$\frac{b_f/t_f}{\varepsilon} \leq 60$

ϕ_{Cd} can be found from graphs in Figure C.1 in EC3-5, pasted below based on results from bending tests with steel sheet piles as well as finite element simulations.ρ_c-curves are plotted in a $(b/t_f/\varepsilon)$-ϕ_{Cd} diagram.

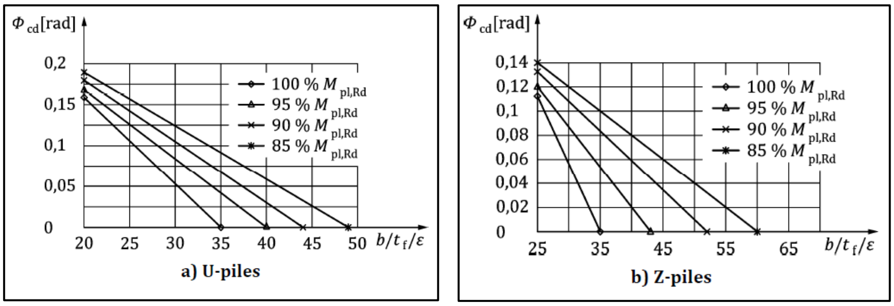


Figure 6 Rotation capacity angle at different levels of reduction of $M_{pl,Rd}$ (Figure C.1 in EC3-5:2024-06-24, Ref. [2])

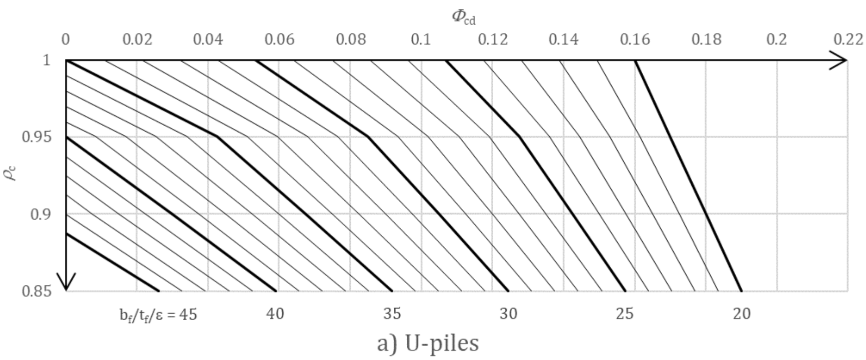
The limiting values on the horizontal axis appear from Table C.1 in EC3-5, cf. Ref. [2].

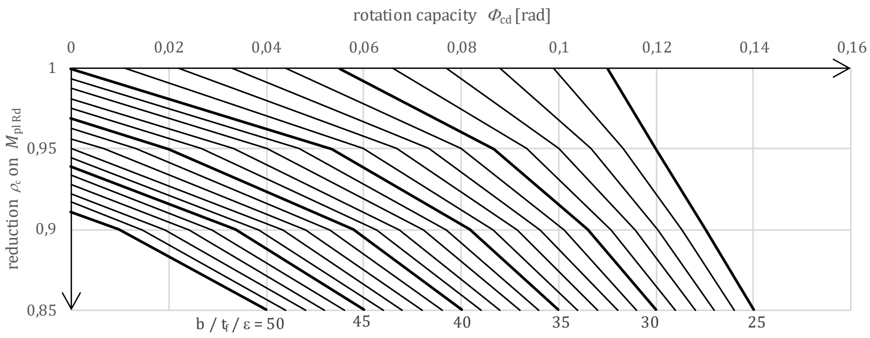
The limiting values on the vertical axis in EC3-5 Figure C.1 appear from Table below.

Table 3 ϕ_{Cd} - values [rad] on vertical axis in Figure C.1 in EC3-5

ρ_c	1,00	0,95	0,90	0,85
U-piles (b_f / t_f / ε = 20)	0,16	0,17	0,18	0,19
Z-piles (b_f / t_f / ε = 25)	0,11	0,12	0,13	0,14

However, in the latest draft of EC3-5 prepared for FV (SC7 Doc N4032, Ref. [3]) the format of Figure C.1 is changed to figures as appear below





b) Z-piles

Figure 7 Rotation capacity depending on slenderness and utilisation ρ_c of plastic bending resistance (Figure C.1 in EC3-5:2024-07-23, Ref. [3])

The figures represent the same data. The idea is to make ease of use. Each line in the figure corresponds to one slenderness ratio (rounded up to a whole number, i.e. an integer, considered to be precise enough for all practical applications). With this slenderness for a particular sheet pile profile you can determine the rotation capacity ϕ_{Cd} for any degree of utilisation of the profile ρ_c between 85 % and 100 % of the plastic bending moment capacity $M_{pl,Rd}$.

However, this form does not facilitate a quantitative determination of the rotation capacity, only a graphically determination, for which reason the SC3-WG responsible for the revision of EC3-5 has provided formulas for ϕ_{Cd} = f($b/t_f/\varepsilon$) for ρ_c = 0,85; 0,90; 0,95 and 1,00 to allow for determination of “knee points” in the new form of Figure C.1, cf. table below.

Table 4 formulas for ϕ_{Cd}, where $\lambda = b/t_f/\varepsilon$

ρ_c	0,85	0,90	0,95	1,00
U-piles	$0{,}19\left[1-\frac{\lambda-20}{29}\right]$	$0{,}18\left[1-\frac{\lambda-20}{24}\right]$	$0{,}17\left[1-\frac{\lambda-20}{20}\right]$	$0{,}16\left[1-\frac{\lambda-20}{15}\right]$
Z-piles	$0{,}14\left[1-\frac{\lambda-25}{35}\right]$	$0{,}13\left[1-\frac{\lambda-25}{27}\right]$	$0{,}12\left[1-\frac{\lambda-25}{18}\right]$	$0{,}11\left[1-\frac{\lambda-25}{10}\right]$

Consistency between Annex C and D in EC3-5

The limiting values of the relative slenderness $\lambda = b_f/t_f/\varepsilon$ in Table 2 represent the maximum utilization of the plastic modulus W_{pl} for a given relative slenderness ratio leaving no (extra) plastic rotation capacity (ϕ_{Cd} = 0). They are consistent with the elasto-plastic section modulus W_{ep} values you can determine from EC3-5, Annex E *Properties of semi-compact sections*.

For Z-piles

$$W_{ep} = W_{pl} + (W_{el} - W_{pl})\frac{b_f/t_f - 35\varepsilon}{25\varepsilon} \qquad \text{(EC3-5, E.1)}$$

Introducing $\lambda = \frac{b_f/t_f}{\varepsilon}$ and dividing by W_{pl} in (E.1) gives:

$$\frac{W_{ep}}{W_{pl}} = 1 + \left(\frac{W_{el}}{W_{pl}} - 1\right)\frac{\lambda - 35}{25}$$

Valid for $35 < \lambda < 60$

For U-piles

$$W_{ep} = W_{pl} + (W_{el} - W_{pl})\frac{b_f/t_f - 35\varepsilon}{14\varepsilon} \qquad \text{(EC3-5, E.2)}$$

Introducing $\lambda = \frac{b_f/t_f}{\varepsilon}$ and dividing by W_{pl} in (E.2) gives:

$$\frac{W_{ep}}{W_{pl}} = 1 + \left(\frac{W_{el}}{W_{pl}} - 1\right)\frac{\lambda - 35}{14}$$

Valid for $35 < \lambda < 49$

W_{ep}/W_{pl} is comparable to ρ_c

If you assume $W_{el}/W_{pl} \sim 0{,}85$ you get a very fine fit of W_{ep}/W_{pl} with ρ_c from Table C.1 in EC3-5 as appear from the table below.

Table 5 ρ_c and W_{ep}/W_{pl} for Z- and U-piles assuming W_{el}/W_{pl} = 0,85

Table C.1	**Z-piles**	E.1	$\frac{\rho_c}{W_{ep}/W_{pl}}$	**U-piles**	E.2	$\frac{\rho_c}{W_{ep}/W_{pl}}$
ρ_c	$b_f/t_f/e$	W_{ep}/W_{pl}	-	$b_f/t_f/e$	W_{ep}/W_{pl}	-
1,00	35	1,000	1,000	35	1,000	1,000
0,95	43	0,952	0,998	40	0,946	1,004
0,90	52	0,898	1,002	44	0,904	0,996
0,85	60	0,850	1,000	49	0,850	1,000

This means that even if you are (just) doing an **elastic** global analysis – and thus not chasing a rotation capacity - you can still utilise a Class 3 section to more than just the pure elastic section modulus capacity, depending on the relative slenderness of the profile.

6. REQUIRED ROTATION

As the rotation capacity ϕ_{Cd} is defined and determined as the plastic rotation beyond the elastic rotation the necessary rotation ϕ_{Ed} is likewise defined as the extra rotation (if needed) beyond the elastic rotation, which makes determination of the elastic rotation relevant.

The necessary (extra) rotation capacity beyond the elastic rotation can be determined in three ways according to EC3-5, Annex C:

1. Direct determination from the rotation in a plastic hinge
2. Based on the total rotation in a span between two supports or
3. Based on the beam displacement at certain points along the span

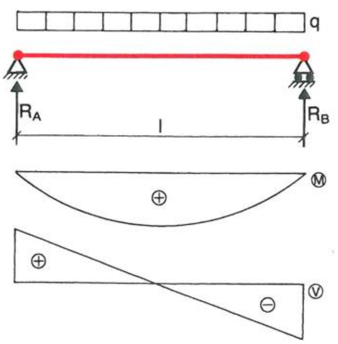
The first option is relevant when analysing / calculating the wall with an elasto plastic finite element program, which allows for direct reading of the plastic rotation of the section with maximum bending moment.

The two last options can be expressed as

$\phi_{Ed} = \phi_{total} - \phi_{elastic}$

where both terms are based on either the rotation or the displacement.

Considering a simply supported beam, the elastic mid (and max) deflection u_{max} and rotation α at the supports from a uniform load q can be expressed as appear from the figure below



$$R_A = R_B = \frac{1}{2}ql\ ;\ M(x) = \frac{1}{2}qx\,(l-x)$$

$$M_{\max} = \frac{1}{8}ql^2 \quad \text{for} \quad x = \frac{1}{2}l$$

$$u(x) = \frac{ql^3x}{24EI}\left(1 - 2\left(\frac{x}{l}\right)^2 + \left(\frac{x}{l}\right)^3\right)$$

$$u_{\max} = \frac{5}{384}\frac{ql^4}{EI} \quad \text{for} \quad x = \frac{1}{2}l$$

$$\alpha_A = -\alpha_B = \frac{1}{24}\frac{ql^3}{EI}$$

Figure 8 elastic rotation and displacement (from Teknisk Ståbi, 25. Udg.)

Substituting $1/8\ q\ L^2$ with M in the expressions for u_{max} and α renders

$u_{max} = \frac{5}{384}\frac{qL^4}{EI} = \frac{5}{48}\frac{ML^2}{EI}$ and $\alpha_A = -\alpha_B = \frac{1}{24}\frac{qL^3}{EI} = \frac{1}{3}\frac{ML}{EI}$

where

$M = \rho_c\, M_{pl.Rd}$ and

$$M_{pl,Rd} = \beta_B W_{pl} \frac{f_y}{\gamma_{M0}}$$

β_B (B for bending) is a reduction factor that takes account of the lack of shear force transmission in the interlocks and oblique bending in double U-piles.

Similarly, the stiffness EI is reduced with a(nother) β-factor: β_D. D for deflection.

β_B and β_D depend on the number of anchors/supports and the soil conditions. Recommended values appear from Table 8.1 (NPD) in EC3-5. For a Z-profile both β-factors are 1,0.

Based on the total rotation in a span between two supports the value of ϕ_{Ed} may be found as

$\phi_{Ed} = \phi_{tot,Ed} - \phi_{y,Ed}$ (C.2 in EC3-5)

where

$\phi_{tot,Ed}$ is illustrated in the figure below and

$\phi_{y,Ed} = \alpha_A - (-\alpha_B) = \alpha_A + \alpha_B = \frac{2}{3}\frac{\rho_c M_{pl,Rd} L}{\beta_D EI}$ (C.3 in EC3-5)

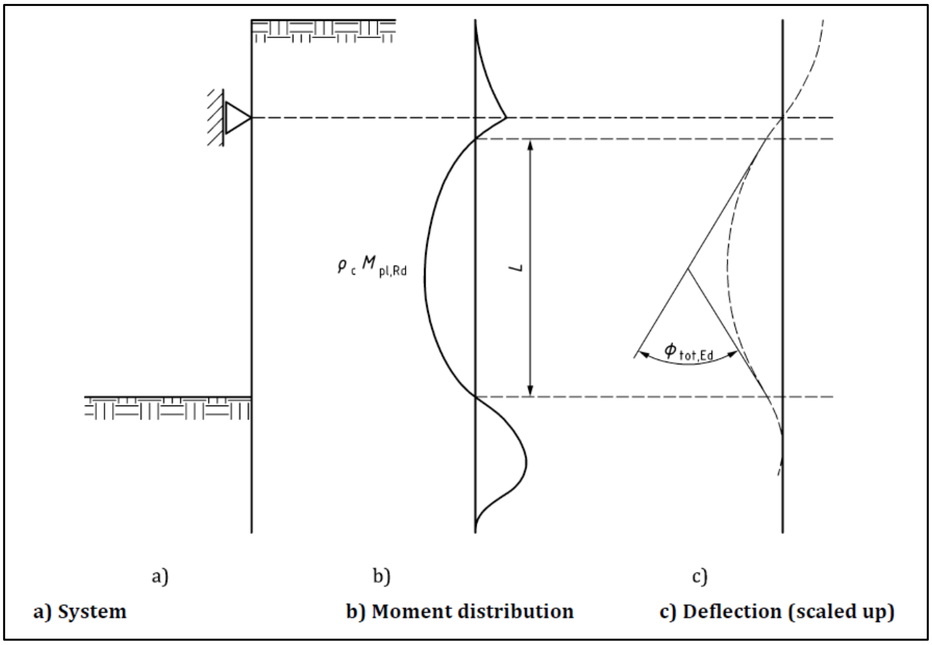


Figure 9 Definition of the total rotation angle $\phi_{rot,Ed}$ using rotation angles (Figure C.3 in EC3-5)

Based on the calculated displacements of the wall the value of ϕ_{Ed} may be found as

$\phi_{Ed} = \phi_{w,Ed} - \phi_{wy,Ed}$ (C.4 in EC3-5)

with

$\phi_{w,Ed} = \frac{w_2 - w_1}{L_1} + \frac{w_2 - w_3}{L_2}$ (C.5 in EC3-5) illustrated in figure below and

$\phi_{wy,Ed} = \frac{u_{max}}{L/2} + \frac{u_{max}}{L/2} = \frac{4}{L} u_{max} = \frac{4}{L} \frac{5}{48} \frac{\rho_c M_{pl,Rd} L^2}{\beta_D EI} = \frac{5}{12} \frac{\rho_c M_{pl,Rd} L}{\beta_D EI}$ (C.6)

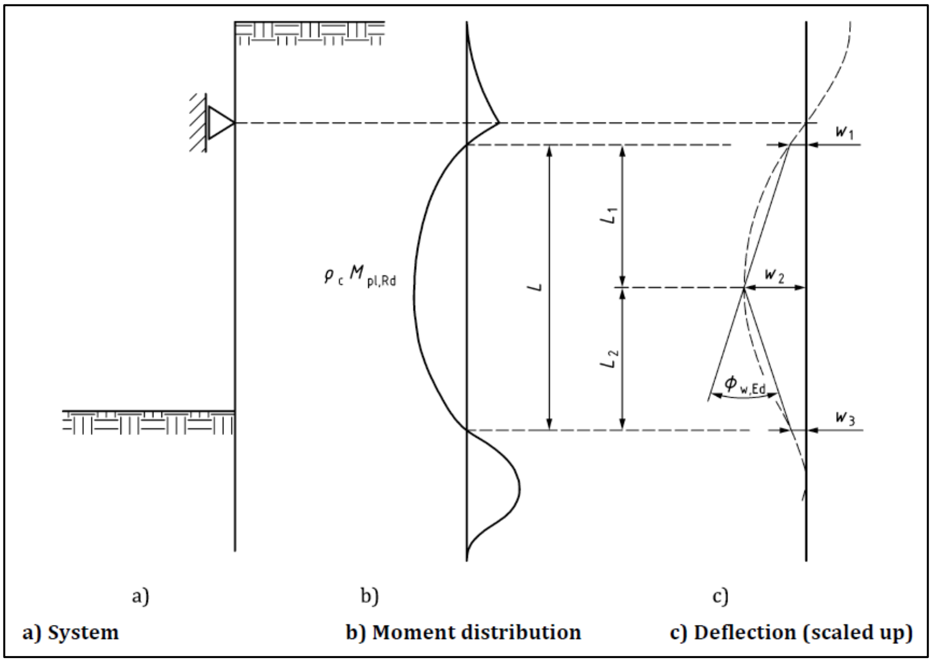


Figure 10 Definition of the total rotation $\phi_{w,Ed}$ based on displacements (Figure C.4 in EC3-5). In the figure an example of a wall with fixed earth support is shown.

The two methods render completely same and exact result (ϕ_{Ed}) for a simply supported beam with a uniform load. The reason for this is, that the two terms in the expression for (ϕ_{Ed}) in (C.2) and (C.4) are both either based on the tangent angle (in C.2) or on the secant angle (in C.4) as illustrated in figure below.

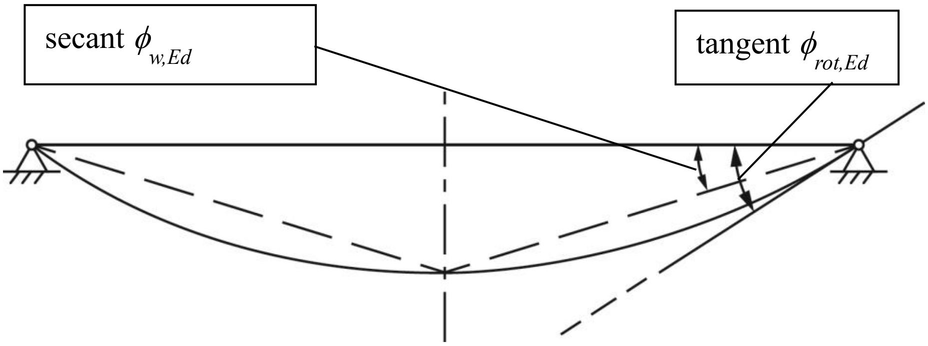


Figure 11 Secant and tangent rotation angles

However, when determining the necessary rotation by a LEM calculation it is practical to use the last/third method based on the displacements of the wall.

Considering three typical failure mechanisms in the figure below and comparing it with figure C.4 in EC3-5 it is a reasonable approximation to calculate the rotation for a wall with one yield hinge (free earth support) as

$$\phi_{w,Ed} = \frac{w_2 - w_1}{L_1} + \frac{w_2 - w_3}{L_2} \approx \frac{v-0}{d} + \frac{v-v}{\infty} = \frac{v}{d}$$

For a wall with two yield hinges (fixed earth support), the rotation is calculated as

$$\phi_{w,Ed} = \phi_1 + \phi_2 = \frac{w_2 - w_1}{L_1} + \frac{w_2 - w_3}{L_2} \approx \frac{v}{d_1} + \frac{v}{d_2}$$

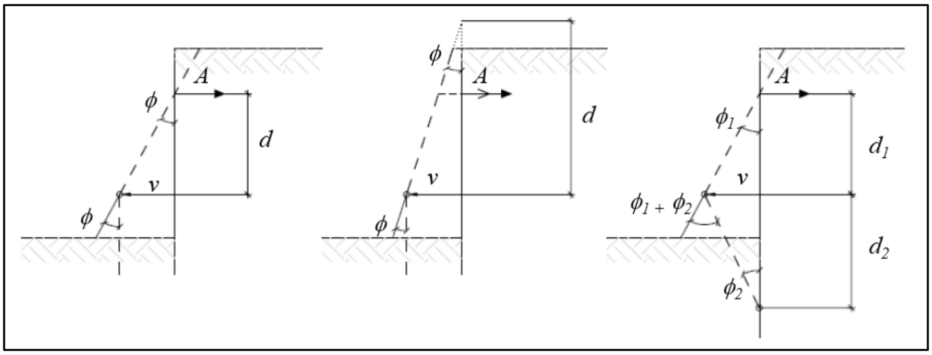


Figure 12 Rotation around rotation points by LEM failure mechanisms

7. EXAMPLE

LEM calculation of anchored wall with one yield hinge.

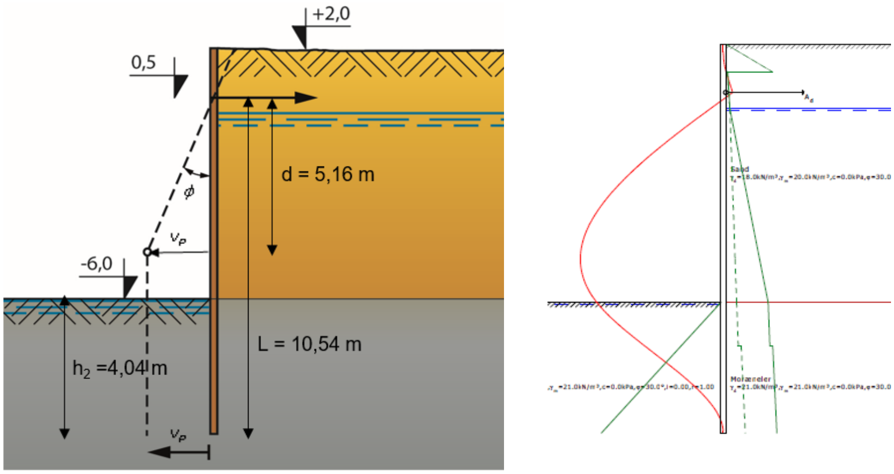


Figure 13 Wall with one yield hinge, bending moment and earth pressure distribution

Results of wall calculation

A_d = 212 kN/m (at level +0,5)

M_{Ed} = **543 kNm/m**

Yield hinge at -4,66

Toe level = -10,04

$h_1 = h_a$ =wall height on back (active) side = 12,04 m ~ 12,0 m

$h_2 = h_p$ =wall height on front (passive) side = 4,04 m ~ 4,0 m

d = distance between anchor and plastic hinge = 5,16 m

L = distance from anchor level to toe level = 10,54 m

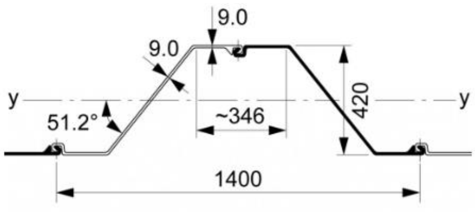
Profile

AZ 18-700

S320 GP ⇒ f_y = 320 MPa

E = 200.000 MPa

I = 37.800 cm^4/m



Cross section Class

$$\varepsilon = \sqrt{235/f_y} = 0{,}857$$

$\lambda = b_f / t_f / \varepsilon = 346 / 9{,}0 / 0{,}857 = 44{,}9 \Rightarrow$ Class 3, cf. Table C.1 in EC3-5

Bending resistance

Z-pile $\Rightarrow \beta_B = \beta_D = 1{,}0$

$W_{el} = 1800\ \text{cm}^3/\text{m} \Rightarrow M_{c,Rd} = M_{el,Rd} = \beta_B\, W_{el}\, f_y/\gamma_{M0} = 524$ kNm/m $< M_{Ed}$!

$W_{pl} = 2116\ \text{cm}^3/\text{m} \Rightarrow M_{c,Rd} = M_{pl,Rd} = \beta_B\, W_{pl}\, f_y/\gamma_{M0} = 616$ kNm/m

Possible reduction factor $\rho_c = M_{Ed}/M_{pl,Rd} = 543/616 = 0{,}88$

($W_{el}/W_{pl} = 0{,}85$ … as usual and claimed)

Rotation capacity ϕ_{Cd}

Draw the 88% $M_{pl,Rd}$ line in the Figure C.1 by interpolation as shown in figure below.

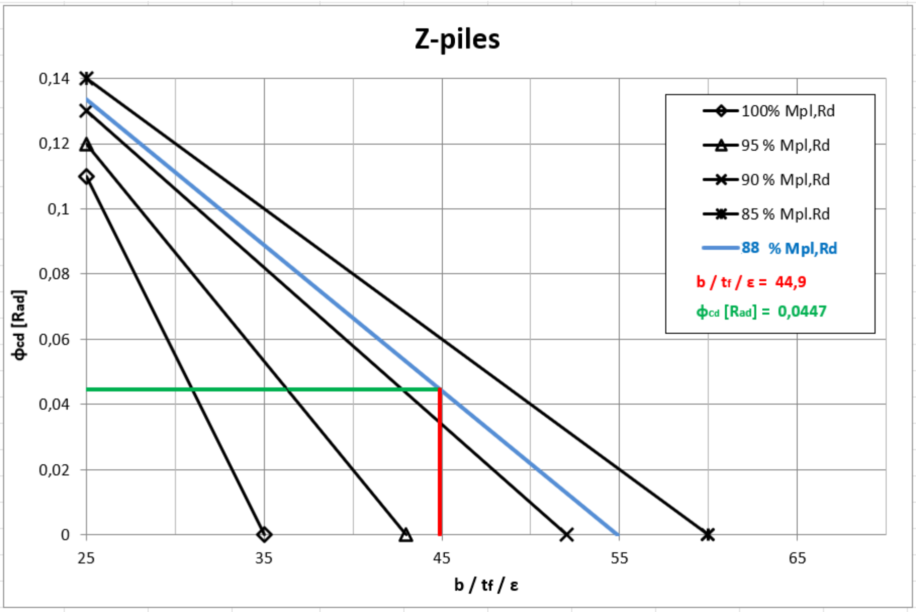


Figure 14 Determination of the rotation capacity ϕ_{Cd} for a given ρ_c and b/t/ε

The intersection between $\lambda = 44{,}9$ and the 88% $M_{pl,Rd}$ line renders a design rotation capacity $\phi_{Cd} = 0{,}0447$ rad = 2,56 deg.

Alternatively, using the new format of Fig. C.1 in EC3-5 from figure below:

$\lambda = 45$ and $\rho_c = 0{,}88 \Rightarrow \phi_{Cd} \sim 0{,}045$ rad = 2,57 deg.

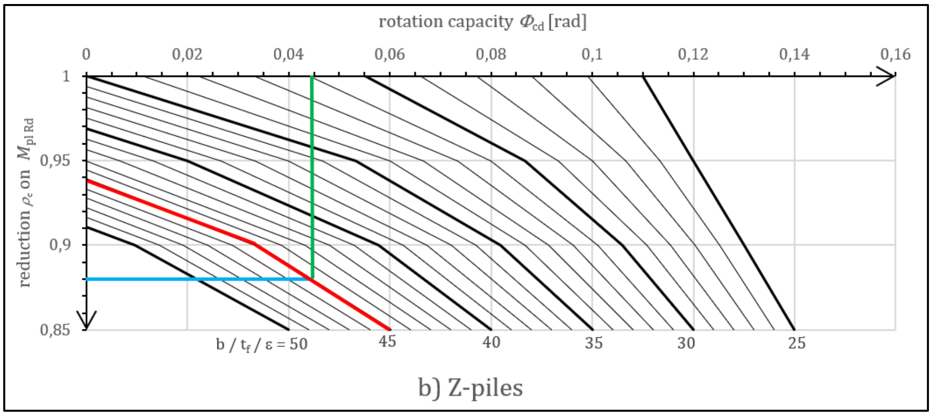


Figure 15 Determination of the rotation capacity ϕ_{Cd} for a given ρ_c and b/t/ε

Mobilisation of plastic earth pressures

Back side (active side):
Assume v_a = 0,3% of h_a = 0,3/100 x 12,0 m = 36 mm

Front side (passive side):
Assume v_p = 5% of h_p = 5/100 x 4,0 m = 200 mm

$v = v_p$ = 200 mm

Required rotation ϕ_{Ed} vs. rotation capacity ϕ_{Cd}

$$\phi_{w,Ed} = \frac{v}{d} = \frac{200}{5160} rad = 0{,}0388\, rad = 2{,}22\, deg$$

$$\phi_{wy,Ed} = \frac{5}{12}\frac{\rho_c M_{pl,Rd} L}{\beta_D EI} = \frac{5}{12}\frac{543 \cdot 10^6 \cdot 10{,}54 \cdot 10^3}{2{,}0 \cdot 10^5 \cdot 37800 \cdot 10^4} = 0{,}0315\, rad = 1{,}80\, deg$$

$\phi_{Ed} = \phi_{w,Ed} - \phi_{wy,Ed}$ = 2,22 deg – 1,80 deg = 0,42 deg < ϕ_{Cd} = 2,56 deg

It is very close that the elastic rotation is enough. If the required displacement to mobilise the passive earth pressure is moderated to say 3% (i.e. 10 x the 0,3% for mobilising the active pressure), a thinner profile like AZ 17-700 being 5% less heavy could have been chosen.

8. CONCLUSIONS

The reliability of the verification of adequate rotation capacity depends on the precision of the determination of the rotation capacity ϕ_{Cd} as well as the necessary rotation ϕ_{Ed}. EC3-5 provides an operational, approximate but experimentally well documented method of determining the rotation capacity, whereas EC7-3 does not provide a similarly precise method for determining the necessary rotation. EC7-3 does give a recommended range of displacement rates to mobilise plastic earth pressures, but the values are a national choice. It is the hope and request from the author that the geotechnical engineers in Europe will work for a more comprehensive, consistent and operational (realistic) set of limiting criteria for mobilising plastic earth pressures in any kind of ground.

ACKNOWLEDGEMENT

Thanks to the MG of SC7: Andrew Bond, Adriaan van Seters, Gunilla Franzén and Geert Kraijema for appointing me as liaison officer for SC7 in SC3/WG18 revising EC3-5. Also, thanks to the PT13 of SC3: Cecile Prüm, Colin Jacobs and Dirk Jan Peters for fruitful dialogue on content of EC3-5 and interface to EC7-3.

REFERENCES

[1] FprEN 1993-5:2024-05-24 Design of steel structures – Part 5: Piling (SC3 Doc N4006).

[2] FprEN 1993-5:2024-06-24 Design of steel structures – Part 5: Piling, (No SC3 doc number, corrected version of N4006).

[3] FprEN 1993-5:2024-07-23 Design of steel structures – Part 5: Piling (SC3 Doc N4032).

[4] FprEN 1997-3:2024 Geotechnical design – Part 3: Geotechnical structures (SC7 Doc N1753), termed EC7-3 in the paper.