Off-centre anchoring of AZ sheet pile walls

Steel Sheet Piling

Steel solutions for a better world

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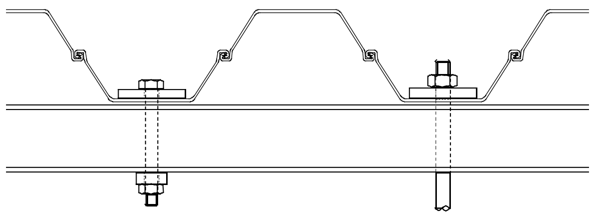
Introduction

The Z-section sheet piles of the AZ series marketed by Arcelor Profil Luxembourg differ from the Z-section sheet piles of competitors and from U-section sheet piles in the following ways:

- the combination of the advantageous Z profile and the time-proven Larssen interlock make them an economical solution with a superior section-modulus-to-weight ratio;

- the favourable position of interlocks on the outer side, on the extreme fibre, overcomes the problem of transmission of shear force in the interlock, making crimping unnecessary to guarantee maximum strength.

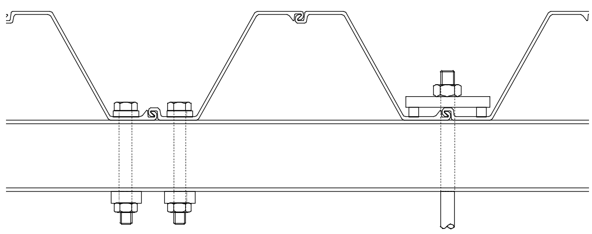
In practice, however, when sheet piles are to be tied back, it is not uncommon for U-section piles to be preferred. This choice is made for detailing reasons: with U-section sheet piles both waling bolts and tie rods can be centred on the back of the pile.



Anchoring of U-section sheet piles

If Z-section piles are used, the interlock running down the centre of the trough results in conservative measures being adopted, with walings being fixed with two bolts, thereby increasing material costs and the complexity – and cost – of installation.

If tie rods are to be centred on the trough, they have to pass through the interlock. This requires a special bearing plate with welded shims to bridge the interlock ridge. If the water table behind the sheet piles reaches the line of tie rods, the hole through the interlock might impair watertightness.



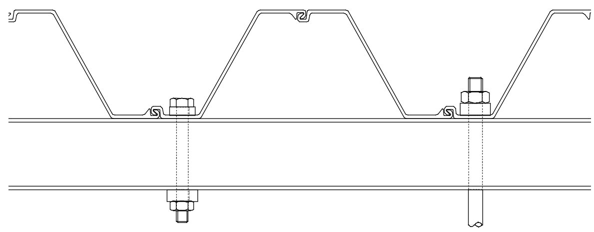
Traditional anchoring of Z piles

An economical solution for anchoring AZ piles

To enable full advantage to be taken of the AZ series sheet piles under the most economical global conditions, Arcelor Profil Luxembourg has developed a financially attractive alternative solution:

off-centre anchoring.

This solution combines the outstanding static properties of AZ sheet piles with the simplicity of the anchorages used with U piles. It simply involves putting the bolts or tie rods through one of the flanges alongside the interlock: this avoids the problem of making a hole through the interlock and using a complex bearing plate.



An economical solution for anchoring AZ sheet piles

The advantage of off-centre anchoring is that it mobilizes the high strength of Z piles without having a hole through the interlock.

The economic advantages are obvious:

- off-centre fixing of walings with a single bolt reduces material and installation costs,

- off-centre positioning of tie rods makes it possible to use plain bearing plates, and having a hole in the flange rather than through the interlock means achieving effective waterproofing ceases to be a problem.

Research project

Until now no design regulations have addressed the possibility of off-centre anchoring of Z-section piles. In close collaboration with the Department of Steel Construction of the RWTH in Aachen, Arcelor therefore undertook a vast research project to analyze the behaviour of sheet piles with off-centre anchoring and to determine the corresponding design rules.

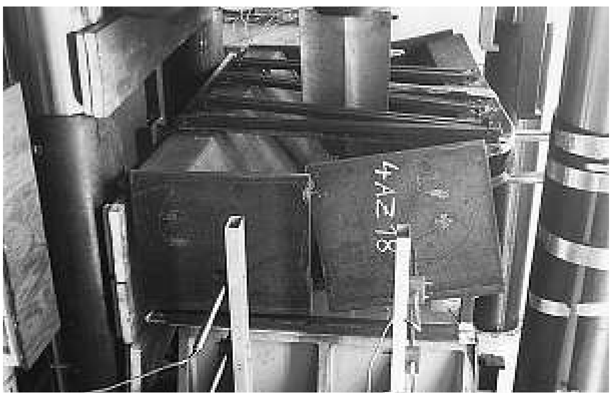
This research project comprised the following steps:

- experimental studies on Z piles subject to off-centre loading,
- finite-element modelling based on the test results,
- analysis of the behaviour of a double sheet pile (in a wall) subject to eccentric loading,
- drafting of a design method.

The results of the study were consigned to a final detailed report [1] and are summarized here for practical application.

Experimental studies

The tests on Z piles where carried out at the RWTH Institute of Ferrous Metallurgy.



Double AZ18 sheet pile during test

Double AZ18 sheet pile after test

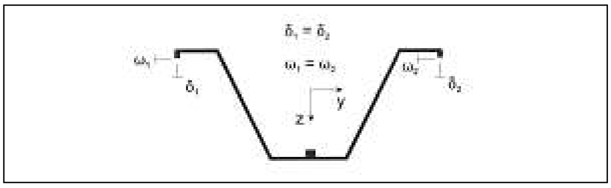
A hydraulic cylinder was used to apply a force representing the anchor force to an off-centre bearing plate. For technical reasons the test could only be carried out on one double-pile unit at a time. To simulate lateral continuity, the two piles were cross-braced.

The photos of AZ18 double piles after the test attest to the ductile behaviour obtained with this solution.

Finite-element model calibration and simulations

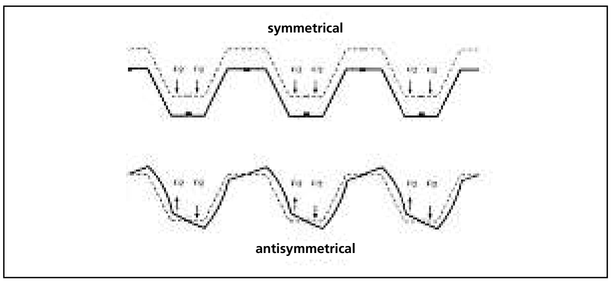
The test results were used to calibrate a finite-element model which was then used for parametric studies. The finite-element simulations were run at the RWTH Department of Steel Construction.

This made it possible to more precisely consider the boundary conditions pertaining to a continuous sheet pile wall, conditions which could only be partially taken into account in the physical tests.



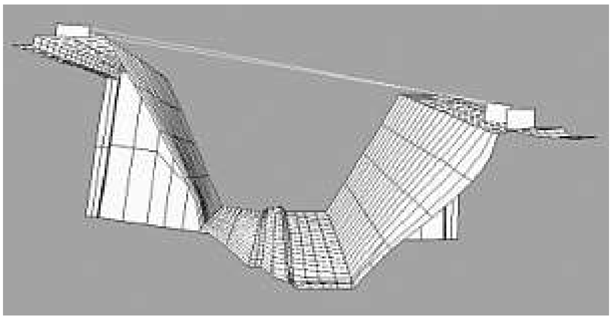
Boundary conditions of a double AZ pile

In principle the local eccentric force can, using a simple model, be broken down into a symmetrical component and an antisymmetrical component.

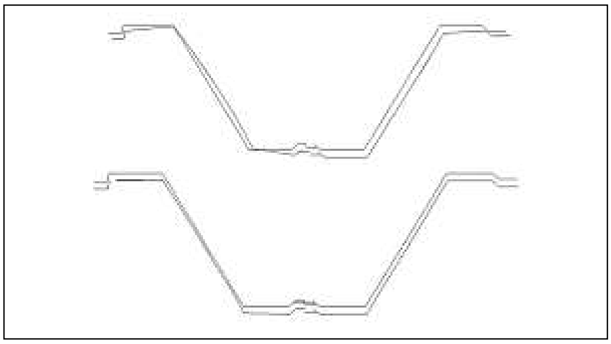


Symmetrical and antisymmetrical components of force

The deformations observed during the physical tests were confirmed by the finite-element studies.

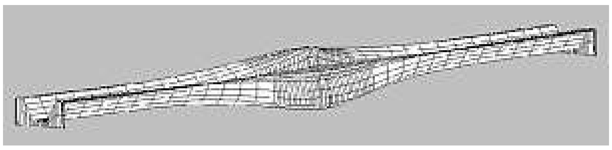


Deformation under eccentric force



Deformation for different parameters

The importance of rotation is affected by different parameters such as the span and the stiffness of the soil behind the sheet pile wall.



Rotation due to the antisymmetrical component of the force (highly exaggerated)

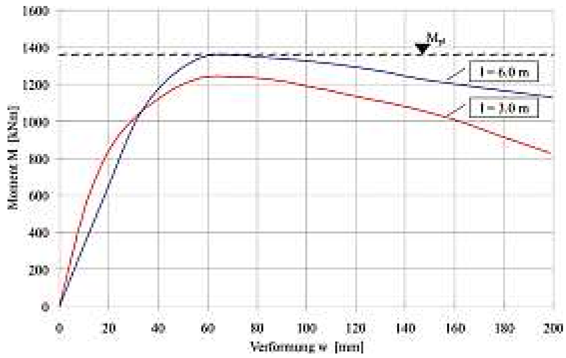
The parametric studies examined several limit states that might arise with eccentric loading under actual boundary conditions:

1. moment resistance of the cross-section at the point of application of eccentric force,

2. interlock resistance (declutching),

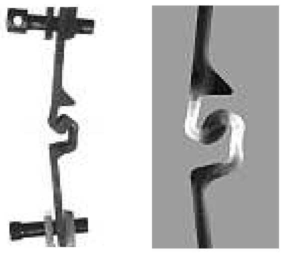
3. shear resistance (punching shear resistance) of flange and tensile resistance of web under local anchor force.

Consequently, the study determined the performance of the cross-section resulting in a reduced moment resistance for different eccentricity factors α_{ex} imposed by the boundary conditions.



Study of moment resistance

Other physical tests were also carried out, and finite-element simulations of interlock behaviour under horizontal tensile forces were run.



Study of interlock strength

Development of a design method

The analysis of test results and finite-element parametric studies served to develop a design method taking account of boundary conditions and indirect actions to which a double Z sheet pile is subject under local eccentric loading. This method complies with European standard EN 1993-5 and covers both local analysis and the effect on overall resistance.

The design method for bearing plates proposed below is based not only on the tests described above but also on another study on the determination of bearing plate sizes [2], also carried out by the RWTH Department of Steel Construction.

Design method and parameters

NB: Off-centre anchoring can also be used in the case of inclined tie rods; the design rules given here concern only the **horizontal component** of anchor force, however.

Procedure:

- Choose dimensions and check bearing plate
- Determine eccentricity factors for each anchor point and check resistance to local forces
- Determine reduction coefficients for each anchor point and check sheet piling at the anchor level and generally.

Choice of bearing plate dimensions

The dimensions of the bearing plate must be chosen within the limits given below:

Width: $\boxed{0.90 \cdot b_c \leq b_a \leq b_c}$

Length: $\boxed{h_a \leq 2.5 \cdot b_a}$

Thickness: $\boxed{t_a = \begin{cases} \geq 40mm \\ \geq 2 \cdot t_F \\ \geq d_A / 3 \end{cases}}$

where : b_c = width of AZ pile flange (between fillet tangent points) **(cf Tab. 3)**
t_F = flange thickness
d_A = nominal diameter of bolt or tie rod

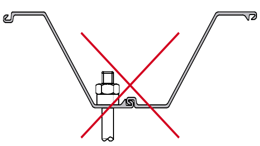
Tab. 1: Bearing plate hole diameters (for guidance only)

Nominal diameter d_A	ϕ mm	d_{sw} mm	d' mm
1.5"	41	60	51
1.75"	48	70	59
2"	54	80	67
2.25"	60	85	73
2.5"	68	95	81
2.75"	74	105	89
3"	81	110	96
3.25"	88	120	104
3.5"	94	130	112

(Dimensions from [3])

Bearing plate position

NB: The anchor and/or bolt must in all cases be in the flange with the overlying interlock.



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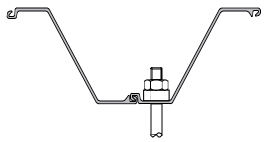

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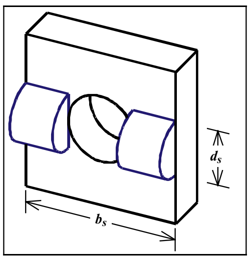
Right positioning of bearing plate



Swivel plate from [3]

Bearing plate check

Note: The following expressions are from report [2].

NB: The design rules given here also apply to inclined tie rods; however, they concern only the **horizontal component** of anchor force.

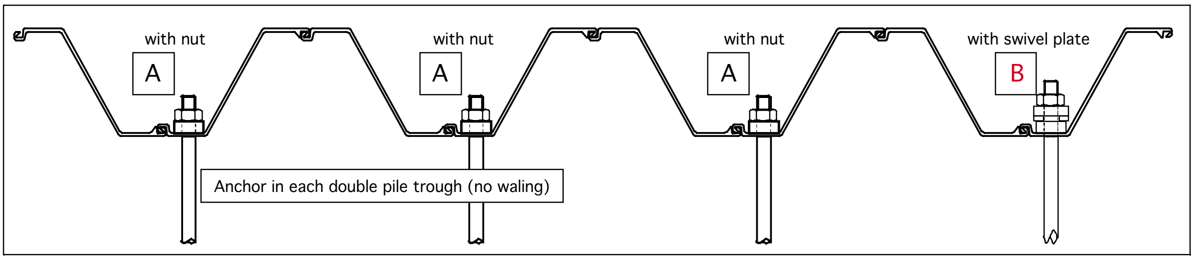
In the case of inclined tie rods, detail appropriately to introduce the vertical component into the sheet pile wall, and make the necessary additional checks.

If alignment brackets are required (when the angles of inclination are steep), their application must be studied case by case.

Bearing plates must be checked in bending. There may be several different situations:

- anchor without waling ➔ **A** (possibly using a swivel plate ➔ **B**)
- bolted waling ➔ **A**
- several sheet piles anchored together, as a unit ➔ **C** (possibly using a swivel plate ➔ **D**)

If there is no waling, there must be an anchor in each trough.



Anchorage without waling

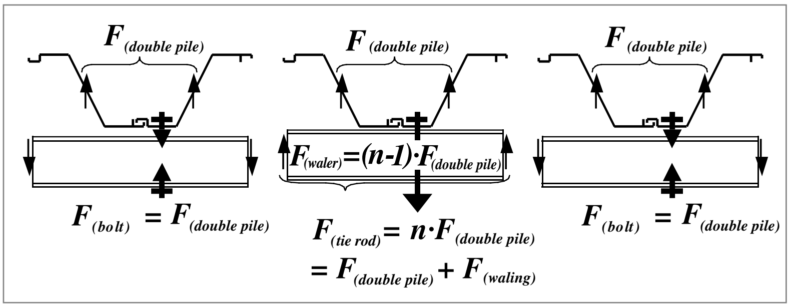
Bearing plate check cases **A** & **B**: no waling, or waling with bolts

$$F_{Ed} \leq F_{Rd,pl} = \frac{4}{3}(b_a - \phi) \cdot X \cdot \left[\sqrt{1+3\left(\frac{t_a}{X}\right)^2} - 1\right] \cdot \frac{f_y}{\gamma_{M0}}$$

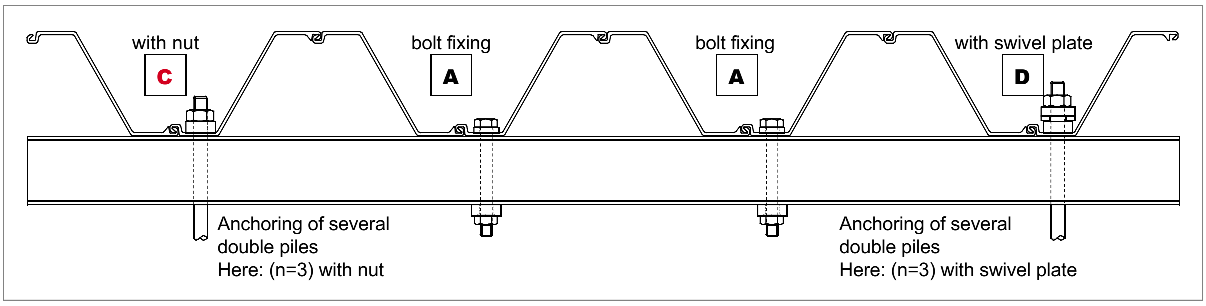
A with nut: $X = h_a - d'$

B with swivel plate: $X = h_a$

If a single tie rod is to anchor several double piles, the off-centre bearing plate must be checked in accordance with C or D. The bearing plates for waling bolts must be checked in accordance with A.



Bolt and anchor forces to be considered



Anchors with bolted waling

Bearing plate check cases **C** & **D**: anchorage of several double piles (n>1)

$$F_{Ed} \le F_{Rd,pl} = \frac{4}{3}\left(b_a - \phi\right)\cdot\frac{n}{2n-1}\cdot X\cdot\left[\sqrt{1+3\left(\frac{t_a}{X}\right)^2}-1\right]\cdot\frac{f_y}{\gamma_{M0}}$$

C with nut: $$X = \frac{h_a - d' + 2(n-1)(s-d')}{2n-1}$$

D with swivel plate: $$X = \frac{h_a + 2(n-1)s}{2n-1}$$

where: for **A** & **B**: F_{Ed} = horizontal component of the anchor force **per double pile**

for **C** & **D**: F_{Ed} = horizontal component of the anchor force **per tie rod**

b_a , h_a , t_a = width / length / thickness of bearing plate

f_y = yield strength of bearing plate

$d' = (d_{SW} + \phi)/2$ = load spread diameter

d_{SW} = bolt head size (spanner size)

ϕ = diameter of hole in bearing plate

n = number of double piles to be anchored

s = distance between waling members

Additional check:

for **A** & **C** (with nut): $$F_{Ed} \le \frac{\pi}{2\sqrt{2}}\left(d_{SW}^2 - \phi^2\right)\frac{f_y}{\gamma_{M0}}$$

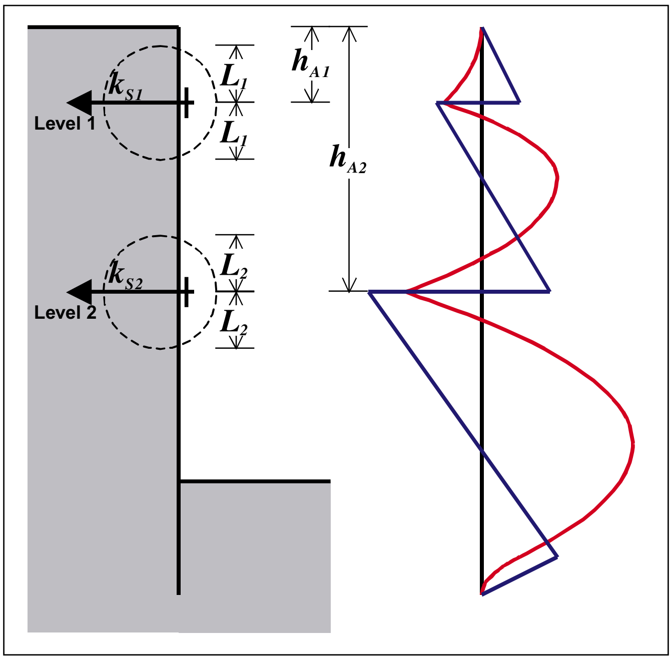
für **B** & **D** (with swivel plate): $$F_{Ed} \le d_s\left(b_X - \phi\right)\frac{f_y}{\gamma_{M0}}$$

where: d_s = diameter of semi-cylindrical lugs (= 50 mm [3])
b_x = min {b_s; b_a}
b_s = width of swivel plate

Eccentricity factor $\alpha_{ex,i}$ at anchor point "*i*"

NB: • If there is more than one level of anchors, α_{ex} must be determined separately for each level.

• The distance between the top anchor level and the top of the sheet piles **must** be at least 1.0 m.



Anchor levels to be considered

Eccentricity factor: $$\boxed{\alpha_{ex,i} = \frac{1}{1+\frac{C_{Sym,i}}{C_{Ant}}}}$$

where: $$\boxed{C_{Sym,i} = k_{s,i} \cdot L_i \cdot \left(0.50 + 1.50\frac{h_{A,i}}{L_i}\right)}$$

for: $\frac{h_{A,i}}{L_i} < 1.00$ with: $\boxed{L_i = \sqrt[4]{4\frac{EI}{k_{s,i}}}}$

$\boxed{C_{Sym,i} = k_{s,i} \cdot L_i \cdot 2}$ for: $\frac{h_{A,i}}{L_i} \geq 1.00$

where: $\alpha_{ex,\,i}$ = eccentricity factor (dimensionless)
$C_{Sym,\,i}$ = stiffness of the system [MN/m²]
L_i = elastic length of tie rod [m]
$h_{A,\,i}$ = distance from anchor level to top of pile [m]
C_{Ant} = torsional stiffness of sheet pile [MN/m²] (**from Tab. 3**)
EI = flexural stiffness of sheet pile wall [MNm²/m] (**from Tab. 3**)
$k_{s,\,i}$ = modulus of soil reaction at the anchor point in question (average over length $2L_i$) [MN/m³] (**cf guideline values in Tab. 2**)

Tab. 2: Guideline values for modulus of soil reaction k_s

Ground type	**k_s MN/m³**
Peat	2
Clay, silty clay, sandy/silty clay	5
Silt	10
Sand loose, moderately compact, compact	40, 80, 150
Gravel	100

NB: • If the soil is stratified, a mean value for k_s at the anchor level must be found.

Tab. 3: Design parameters for AZ sheet piles with off-centre anchors

Sheet piles	Flange width b_c mm	Plate width b_a mm	EI MNm²/m	C_{Ant} MN/m²	Double pile width B m	Flange thick-ness t_F mm	Web thick-ness t_W mm	$t_{W'}$ cm/m	Interlock charac-teristic K_L mm	C_{Ex} mm	W_{pl} cm³/m	W_{el} cm³/m	A_V cm²/m	α [°]	L_{Ex} m	Classification as per EN 1993-5 S 235	S 270	S 320	S 355	S 390	S 430
AZ 12	154	145-150	38.1	31.0	1.34	8.5	8.5	**1.269**	1.38	1.90	1409	1200	36.2	45.4	5.5	2	3	3	3	3	3
AZ 13			41.4	39.5		9.5	9.5	**1.418**		2.38	1528	1300	40.3			2	2	2	3	3	3
AZ 14			44.7	50.9		10.5	10.5	**1.567**		2.90	1651	1400	44.4			2	2	2	2	2	3
AZ 17	147	135-145	66.3	38.3	1.26	8.5	8.5	**1.349**	1.85	2.68	1944	1665	48.8	55.4	7.0	2	2	3	3	3	3
AZ 18			71.8	48.3		9.5	9.5	**1.508**		3.34	2104	1800	54.4			2	2	2	3	3	3
AZ 19			77.7	62.8		10.5	10.5	**1.667**		4.08	2275	1940	60.0			2	2	2	2	2	2
AZ 25	132	120-130	109.7	82.6	1.26	12	11.2	**1.778**	2.17	4.58	2873	2455	71.5	58.5	6.0	2	2	2	2	2	2
AZ 26			116.6	106.5		13	12.2	**1.937**		5.38	3059	2600	77.7			2	2	2	2	2	2
AZ 28			123.8	120.6		14	13.2	**2.095**		6.24	3252	2755	83.8			2	2	2	2	2	2
AZ 34	143	130-140	165.3	130.5	1.26	17	13	**2.063**	2.37	8.57	3980	3430	87.7	63.4	6.0	2	2	2	2	2	2
AZ 36			173.9	153.1		18	14	**2.222**		9.60	4196	3600	94.2			2	2	2	2	2	2
AZ 38			182.9	181.0		19	15	**2.381**		10.70	4417	3780	100.7			2	2	2	2	2	2
AZ 36 n	168	155-165	188.5	62.9	1.40	17	11.2	**1.600**	2.34	7.22	4098	3597	74.4	63.2	6.5	2	2	2	2	2	2
AZ 38 n			199.2	76.7		18	12.2	**1.743**		8.10	4353	3793	80.9			2	2	2	2	2	2
AZ 40 n			209.9	91.4		19	13.2	**1.886**		9.02	4614	3989	87.3			2	2	2	2	2	2
AZ 46	147	135-145	231.9	221.4	1.16	18	14	**2.414**	2.76	10.39	5295	4595	107.4	71.5	6.0	2	2	2	2	2	2
AZ 48			242.9	248.6		19	15	**2.586**		11.58	5553	4800	114.8			2	2	2	2	2	2
AZ 50			254.2	285.2		20	16	**2.759**		12.83	5816	5015	122.2			2	2	2	2	2	2

Check of resistance of AZ sheet pile wall to local force

The design resistance of sheet piling to local force (at each off-centre anchor point) must be checked.

$$\boxed{F_{Ed,i} \leq R_{Rd,Ex,AZ} = \frac{\min\left(R_{Lock,Rk}; R_{Vf,Rk}; R_{tw,Rk}\right)}{\gamma_{M0}}}$$

where:

$$\boxed{R_{Vf,Rk} = (h_a + b_a) \cdot t_F \cdot \frac{f_y}{\sqrt{3}} \cdot (1 + \alpha_{ex,i})}$$ punching shear resistance of flange

$$\boxed{R_{tw,Rk} = h_a \cdot t_W \cdot f_y \cdot (1 + \alpha_{ex,i})}$$ tensile resistance of web

$$\boxed{R_{Lock,Rk} = (h_a + 2b_a) \cdot K_L \cdot f_u \cdot \frac{1}{1 - \alpha_{ex,i}}}$$ interlock resistance

In the expressions above:

$F_{Ed,i}$ = F'_{Ed} · B = anchor force applied, **per double pile**

F'_{Ed} = anchor force applied (horizontal component) **(per linear metre)**

B = width of double pile (**from Tab. 3**)

K_L = interlock characteristic coefficient (**from Tab. 3**)

t_F, t_W = flange thickness / web thickness (**from Tab. 3**)

b_a, h_a = width / length of bearing plate

f_y, f_u = yield strength / ultimate tensile strength of AZ sheet piles (**from Tab. 4**)

$\alpha_{ex,i}$ = eccentricity factor at anchor point concerned

NB: For the interlock resistance $R_{Lock,Rd}$, take f_u (ultimate tensile strength).

Tab. 4: AZ sheet pile steel grades

Grade (as per EN 10248)	Yield strength f_y [N/mm²]	Ultimate tensile strength f_u [N/mm²]
S 240 GP	240	340
S 270 GP	270	410
S 320 GP	320	440
S 355 GP	355	480
S 390 GP	390	490
S 430 GP	430	510

NB: For F_{Ed}, take the horizontal component of the anchor force introduced into the double pile (cf diagram on page 7).

Note: The expressions above, especially K_L, are derived from equations (5.23), (5.24), and (5.25) in document [1].

Reduction coefficients $\beta_{ex,i}$ at anchor point "*i*"

At the anchor point "*i*" considered:

$$\boxed{\beta_{ex,i} = \sqrt{1 - (1 - \alpha_{ex,i}) \frac{F_{Ed,i}}{C_{Ex} \cdot f_y}}}$$

where:
- $\beta_{ex,i}$ = reduction coefficient at anchor point "*i*"
- $\alpha_{ex,i}$ = eccentricity factor at anchor point
- $F_{Ed,i}$ = horizontal component of anchor force applied (**per linear metre of sheet pile wall**)
- f_y = yield strength of AZ sheet pile (**from Tab. 4**)
- C_{Ex} = characteristic value for transverse bending of sheet pile (**from Tab. 3**)

If there is more than one level of anchors, $\beta_{ex,i}$ must be determined separately for each level.

Note: In the case of retaining walls combining off-centre anchors and centred anchors or braces, take β_{ex} =1.0 at centred anchor or bracing points.

Check of bending moment and shear capacity of sheet piling at anchor point

Classes 1 and 2: $$\boxed{M_{Ed} \leq M_{c,Rd} = \beta_{ex,i} \cdot W_{pl,Net} \cdot \frac{f_y}{\gamma_{M0}}}$$

$$W_{pl,Net} = W_{pl,Gross} \cdot r_{W,pl}$$

$$r_{W,pl} = 1.0 - 0.8 \cdot \phi$$

Class 3: $$\boxed{M_{Ed} \leq M_{c,Rd} = \beta_{ex,i} \cdot W_{el,Net} \cdot \frac{f_y}{\gamma_{M0}}}$$

$$W_{el,Net} = W_{el,Gross} \cdot r_{W,el}$$

$$r_{W,el} = 1.0 - 1.3 \cdot \phi$$

and: $$\boxed{V_{Ed} \leq V_{Rd} = \beta_{ex,i} \cdot \frac{A_V}{\sqrt{3}} \cdot \frac{f_y}{\gamma_{M0}}}$$

and also, for: $\frac{V_{Ed}}{V_{Rd}} > 0.50$: M-V interaction: $M_{Ed} \leq M_{V,Rd} = \beta_{ex,i} \cdot \left(W_{pl,Net} - \frac{\rho \cdot A_V^2}{4 t_{w'} \sin\alpha} \right) \cdot \frac{f_y}{\gamma_{M0}}$

where: $\rho = \left(2 \frac{V_{Ed}}{V_{Rd}} - 1 \right)^2$

In the expressions above:

M_{Ed}	= bending moment in cross-section considered [kNm/m]
V_{Ed}	= shear force in cross-section considered [kN/m]
W_{el}, W_{pl}	= elastic/plastic section modulus of AZ sheet pile [cm³/m] (from Tab. 3)
A_V	= shear area of AZ sheet pile [cm²/m] (from Tab. 3)
α	= angle of AZ sheet pile web [°] (from Tab. 3)
f_y	= yield strength of AZ sheet pile (from Tab. 4)
r_W	= reduction coefficient (dimensionless) to take account of reduction of cross-sectional area at anchor point
ϕ	= diameter of hole in AZ sheet pile [m]
$\beta_{ex, A, i}$	= reduction coefficient to take account of eccentricity at anchor point.
$t_{w'}$	= $2 \cdot t_w / B$ [cm/m]

Checks of general sections of sheet pile wall

Simplified, taking: $\beta_{ex,F} = \min \beta_{ex,i}$

Classes 1 and 2: $\boxed{M_{Sd} \le M_{c,Rd} = \beta_{ex,F} \cdot W_{pl} \cdot \frac{f_y}{\gamma_{M0}}}$

Class 3: $\boxed{M_{Sd} \le M_{c,Rd} = \beta_{ex,F} \cdot W_{el} \cdot \frac{f_y}{\gamma_{M0}}}$

and: $V_{Sd} \le V_{Rd} = \beta_{ex,F} \cdot \frac{A_V}{\sqrt{3}} \cdot \frac{f_y}{\gamma_{M0}}$

On condition that there is no other reduction in cross-sectional area, the gross section modulus values can be used.

To check general sections (above, below, and between anchorages), and to simplify matters while still staying on the safe side, the smallest of the values for $\beta_{ex,i}$ at adjacent anchor points can be taken for $\beta_{ex,F}$. More favourable values can be determined as explained below.

More precise determination of $\beta_{ex,F}$ in general sections

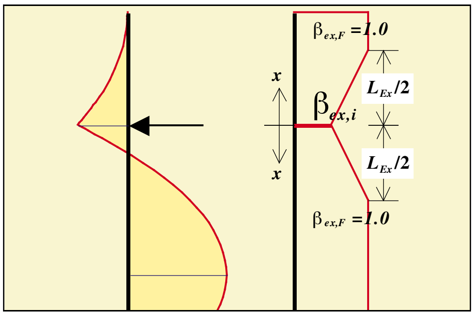
More favourable reduction coefficients, $\beta_{ex,F}$, can be determined for general sections by taking account of: the distance between the anchor point and the section considered; where applicable, the distance L_A between two adjacent layers of anchors; and the cross-section with the maximum bending moment.

a) Single anchored sheet pile walls, or sections above the top anchor layer / below the bottom anchor layer

maximum moment for $x \ge L_{Ex}/2$: $\beta_{ex,F} = 1{,}0$

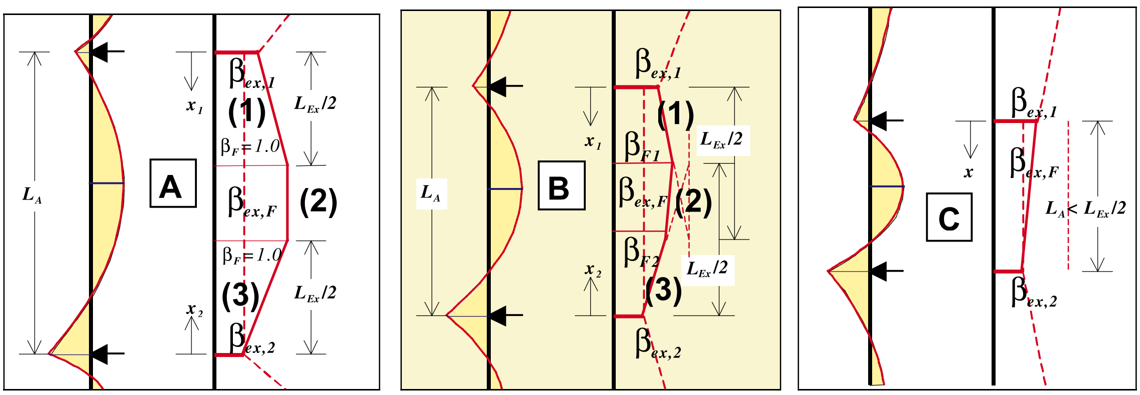
maximum moment for $x < L_{Ex}/2$: interpolation between $\beta_{ex,i}$ and $\beta_{ex,F} = 1{,}0$

where: x = distance between anchor point and section with maximum moment (in general section)
L_{Ex} = reference length of sheet pile (**from Tab. 3**)



Zone of reduction in bending moment resistance

b) Multiple anchored sheet pile walls, between 2 adjacent anchor layers A1 and A2



Zone of reduction in bending moment resistance in the case of several layers of off-centre anchors

where: L_A = distance between the two adjacent layers of anchors

A) Extreme case (large distance): $\boxed{L_A \ge L_{Ex}}$

maximum moment for $x_1 \le L_{Ex}/2$ - zone (1)-: linear interpolation between $\beta_{ex,1}$ & $\beta_{ex,F} = 1{,}0$

maximum moment in zone (2): $\beta_{ex,F} = 1{,}0$

maximum moment for $x_2 \le L_{Ex}/2$ - zone (3) -: linear interpolation between $\beta_{ex,2}$ & $\beta_{ex,F} = 1{,}0$

B) Normal case: $\boxed{L_{Ex} \geq L_A \geq L_{Ex}/2}$

maximum moment for $x_1 \leq L_A - L_{Ex}/2$ - zone (1) -: linear interpolation between

$\beta_{ex,1}$ & $\beta_{F,1} = \beta_{ex,1} + (1 - \beta_{ex,1}) \cdot (\frac{2 \cdot L_A}{L_{Ex}} - 1)$

maximum moment in zone (2): linear interpolation between $\beta_{F,1}$ & $\beta_{F,2}$

maximum moment for $x_2 \leq L_A - L_{Ex}/2$ - zone (3) -: linear interpolation between

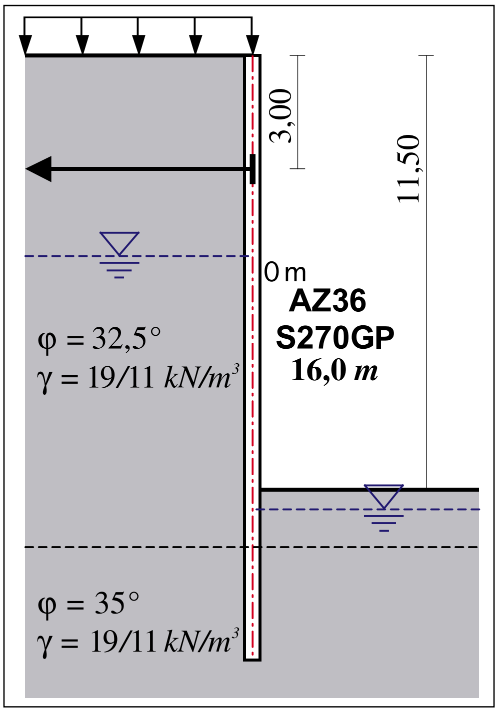
$\beta_{ex,2}$ & $\beta_{F,2} = \beta_{ex,2} + (1 - \beta_{ex,2}) \cdot (\frac{2 \cdot L_A}{L_{Ex}} - 1)$

C) Extreme case (short distance): $\boxed{L_A < L_{Ex}/2}$

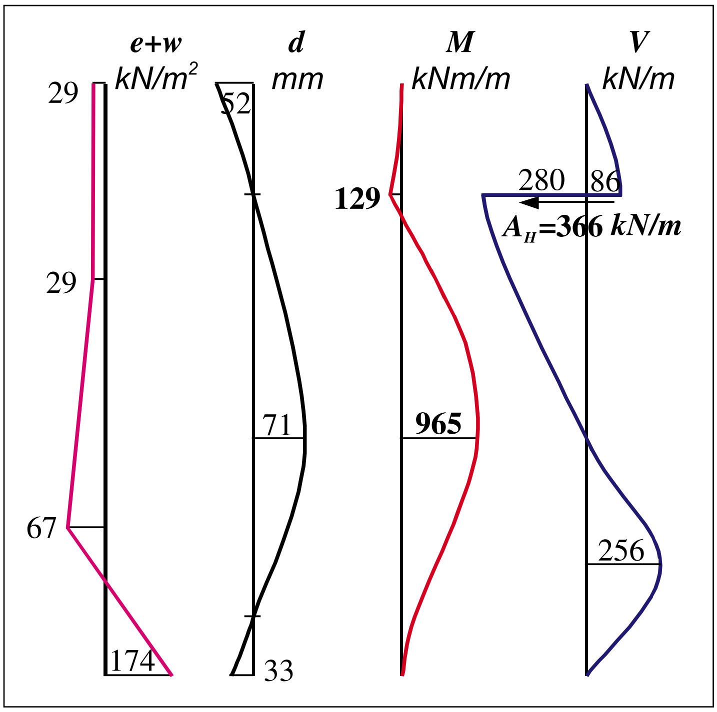
In all of general section: linear interpolation between $\beta_{ex,1}$ & $\beta_{ex,2}$

Example of design

System and action effects



System



Results of numerical calculation (design values)

It is proposed to anchor every second double pile.

It is proposed to install horizontal tie rods: smooth bars with threaded upset ends, with swivel plate to cater for possible settlements.

Intermediate double sheet piles will be bolted to a waling consisting of two 300 mm channel sections set 160 mm apart.

Choice of bolt, tie rod, and bearing plate dimensions

Waling: F_{Ed} = 1,26 • 366 = 461 kN / double pile
choice: bolt d_A = 2,25" (no calculation)
choice: plate b_a / h_a / t_a = 140 / 220 / 40 mm / S355JR

Anchor: F_{Ed} = 2 • 1,26 • 366 = 922 kN / double pile
choice: tie rod d_A = 3,0" (no calculation)
choice: plate b_a / h_a / t_a = 140 / 220 / 85 mm / S355JR

In this example no check is carried out for the bolts and tie rods. It is assumed that the steel grade chosen will withstand the critical design forces.

Bearing plate dimension check

$$b_a = 140\ mm \begin{cases} \le b_c = 143 \text{ mm} \\ \ge 0{,}90 \cdot b_c = 129 \text{ mm} \end{cases} \qquad h_a = 220\ mm \le 2{,}5 \cdot b_a = 350 \text{ mm}$$

Bolt bearing plates:

$$t_a = 40\ mm \begin{cases} \ge 2 \cdot t_F = 36 \text{ mm} \\ \ge \min t_a = 40 \text{ mm} \\ \ge d_A / 3 = 19 \text{ mm} \end{cases}$$

Tie rod bearing plates:

$$t_a = 85\ mm \begin{cases} \ge 2 \cdot t_F = 36 \text{ mm} \\ \ge \min t_a = 40 \text{ mm} \\ \ge d_A / 3 = 25 \text{ mm} \end{cases}$$

where: $\gamma_{M0} = 1{,}0$

Check of bolt bearing plate in bending

With: $d_A = 2{,}25''$ $\quad \phi = 60\ mm$ $\quad d' = 73\ mm$

and (type **A**): $X = h_a - d' = 220 - 73 = 147\ mm$

$$F_{Ed} \le F_{Rd,pl} = \frac{4}{3}(b_a - \phi)X \cdot \left(\sqrt{1 + 3\left(\frac{t_a}{X}\right)^2} - 1\right) \cdot \frac{f_y}{\gamma_M} = \frac{4}{3}(140 - 60) \cdot 147 \cdot \left(\sqrt{1 + 3\left(\frac{40}{147}\right)^2} - 1\right) \cdot \frac{355}{1000 \cdot 1{,}0} = 587\ kN > 461 \text{ kN}$$

Additional check:

$$F_{Ed} \le \frac{\pi}{2\sqrt{2}}\left(d_{SW}^2 - \phi^2\right)\frac{f_y}{\gamma_M} = \frac{\pi}{2\sqrt{2}}\left(85^2 - 60^2\right)\frac{355}{1000 \cdot 1{,}0} = 1429\ kN > 461 \text{ kN}$$

Check of tie rod bearing plate in bending

With : $n = 2$ $\quad s = 160\ mm$

$d_A = 3{,}0''$ $\quad \phi = 81\ mm$

and (Typ **D**):

$$X = \frac{h_a + 2(n-1)s}{2n-1} = \frac{220 + 2 \cdot 1 \cdot 160}{3} = 180\ mm$$

$$F_{Ed} \le F_{Rd,pl} = \frac{4}{3}(b_a - \phi)\frac{n}{2n-1}X \cdot \left(\sqrt{1 + 3\left(\frac{t_a}{X}\right)^2} - 1\right) \cdot \frac{f_y}{\gamma_M} = \frac{4}{3}(140 - 81)\frac{2}{3}180 \cdot \left(\sqrt{1 + 3\left(\frac{85}{180}\right)^2} - 1\right) \cdot \frac{355}{1000 \cdot 1{,}0} = 978\ kN > 922 \text{ kN}$$

Additional check:

$$F_{Ed} \le d_s(b_a - \phi)\frac{f_y}{\gamma_M} = 50 \cdot (140 - 81)\frac{355}{1000 \cdot 1{,}0} = 1047\ kN > 922 \text{ kN}$$

Determination of eccentricity factor

AZ-Profil: $AZ36$ ➔ $EI = 173{,}88\ MNm^2/m$

$C_{Ant} = 153{,}15\ MN/m^2$

Ground at anchor level: moderately compact sand ➔ $k_s = 80\ MN/m^3$

Anchor level: $h_A = 3{,}0\ m$

$$L_i = \sqrt[4]{4\frac{EI}{k_s}} = 1{,}72\ m \qquad \to \frac{h_A}{L_i} = 1{,}75 \geq 1{,}00$$

$$\to C_{Sym} = k_s \cdot L_i \cdot 2 = 275 MN/m^2$$

$$\to \alpha_{ex} = \frac{1}{1 + \frac{C_{Sym}}{C_{Ant}}} = 0{,}36$$

Check of the resistance of the AZ36 pile to local forces

$$R_{Lock,Rk} = (h_a + 2b_a)\cdot K_L \cdot f_u \cdot \frac{1}{1-\alpha_{ex}} = (220 + 2\cdot 140)\cdot 2{,}37 \cdot \frac{410}{1000}\cdot\frac{1}{1-0{,}36} = 759\ kN$$

$$R_{Vf,Rk} = (h_a + b_a)\cdot t_F \cdot \frac{f_y}{\sqrt{3}}\cdot(1+\alpha_{ex}) = (220+140)\cdot 18 \cdot \frac{270}{1000\sqrt{3}}\cdot(1+0{,}36) = 1374\ kN$$

$$R_{tw,Rk} = h_a \cdot t_W \cdot f_y \cdot (1+\alpha_{ex}) = 220\cdot 14\cdot\frac{270}{1000}\cdot(1+0{,}36) = 1131\ kN$$

$$\to F_{Ed} = 461\ kN \leq R_{Rd,Ex,AZ} = \frac{\min\left(R_{Lock,Rk}; R_{Vf,Rk}; R_{tw,Rk}\right)}{\gamma_{M0}} = \frac{759}{1{,}0} = 759\ kN$$

Note: This check is valid for bearing plates for both bolts and anchors since their dimensions b_a and h_a are the same.

Reduction coefficient β_{ex} at anchor point

$$\beta_{ex} = \sqrt{1-(1-\alpha_{ex})\frac{F_{Ed}}{C_{Ex}\cdot f_y}} = \sqrt{1-(1-0{,}36)\frac{366}{9{,}60\cdot 355}} = 0{,}96$$

Check of action effects at anchor point

AZ sheet pile: $AZ36\ /\ S270GP$ ➔ $W_{el} = 3600\ cm^3/m$ ➔ $A_V = 94{,}2\ cm^2/m$

Although the sheet pile can be deemed to be class 1-2 under EN 1993-5, to be on the safe side the check is carried out for the elastic moment resistance.

with: $\phi = 81\ mm$ (it is assumed that the most critical condition is that corresponding to the greatest reduction in the sectional area, at the level of the anchor).

$$W_{el,Net} = W_{el,Gross}\cdot r_{W,el} = 3600\cdot(1.0 - 1{,}3\cdot 0{,}081) = 3221\ cm^3/m$$

$$M_{Ed} \leq M_{c,Rd} = \beta_{ex,A}\cdot W_{el,Net}\cdot\frac{f_y}{\gamma_{M0}} = 0{,}96\cdot 3221\cdot\frac{270}{1000\cdot 1{,}0} = 835\ kNm/m > 129\ \text{kNm/m}\ (\checkmark)$$

$$V_{Ed} \leq V_{Rd} = \beta_{ex,A}\cdot\frac{A_V}{\sqrt{3}}\cdot\frac{f_y}{\gamma_{M0}} = 0{,}96\cdot\frac{94{,}2}{\sqrt{3}}\cdot\frac{270}{10\cdot 1{,}0} = 1410\ kN/m > 280\ \text{kN/m}\ (\checkmark) \quad \frac{V_{Ed}}{V_{Rd}} = 0{,}20 \leq 0{,}50\ (\checkmark)$$

Check of action effects in general sections

To simplify matters (with $\beta_{ex,F} = \beta_{ex,A}$):

$$M_{c,Rd} = \beta_{ex,A} \cdot W_{el} \cdot \frac{f_y}{\gamma_{M0}} = 0{,}96 \cdot 3600 \cdot \frac{270}{1000 \cdot 1{,}0} = 933\ kNm/m < M_{Ed} = 965\ \text{kNm/m}$$

With a more precise value for $\beta_{Ex,F}$:

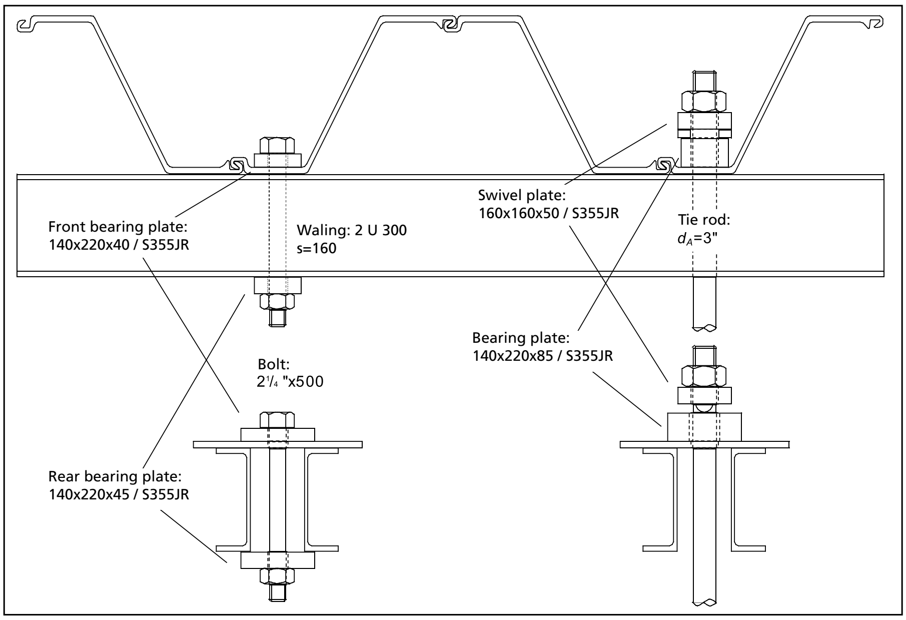
x = 6,60m (distance between tie rod and section with maximum moment):

$$L_{Ex} = 6{,}0\ m \quad \rightarrow \quad x > \frac{L_{Ex}}{2} = 3{,}0\ m \quad \rightarrow \quad \beta_{ex,F} = 1{,}0$$

$$M_{Ed} \leq M_{c,Rd} = \beta_{ex,A} \cdot W_{el} \cdot \frac{f_y}{\gamma_{M0}} = 1{,}0 \cdot 3600 \cdot \frac{270}{1000 \cdot 1{,}0} = 972\ kNm/m > 965\ \text{kNm/m}\ (\checkmark)$$

Note: With $\beta_{ex,F} = \beta_{ex,A}$ and taking the plastic moment resistance, the check would also be met: $M_{Ed} \leq M_{c,Rd}$ = 1088 kNm / m > 965 kNm/m.

Moreover, assuming $\beta_{ex,F} = 1{,}0$ the result is even $M_{Ed} \leq M_{c,Rd}$ = 1133 kNm / m > 965 kNm/m.



System diagram

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