Off-centre anchoring of AZ sheet pile walls

Steel Sheet Piling

Sheet Piling
Arcelor Commercial RPS S.à r.l.
66, rue de Luxembourg
L-4221 Esch-sur-Alzette (Luxembourg)
Tel. +352 5313 3105
Fax +352 5313 3290
E-mail sheet-piling@arcelor.com
www.arcelor.com/sheetpiling
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 Larsen 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.

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.

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.

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.
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.

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.

In principle the local eccentric force can, using a simple model, be broken down into a symmetrical component and an antisymmetrical component.
The deformations observed during the physical tests were confirmed by the finite-element studies.

Consequently, the study determined the performance of the cross-section resulting in a reduced moment resistance for different eccentricity factors $\alpha_w$ imposed by the boundary conditions.

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

### 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.

---

The importance of rotation is affected by different parameters such as the span and the stiffness of the soil behind the sheet pile wall.
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:** \[0.90 \cdot b_i \leq b_a \leq b_c\]
- **Length:** \[h_a \leq 2.5 \cdot b_a\]
- **Thickness:** \[t_a \begin{align*} \geq 40 \text{mm} \\ \geq 2 \cdot t_f \\ \\ \geq d_a / 3 \end{align*}\]

where:  
- \(b_i\) = 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

**Bearing plate position**

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

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

<table>
<thead>
<tr>
<th>Nominal diameter (d_a)</th>
<th>(\phi) mm</th>
<th>(d_{aw}) mm</th>
<th>(d') mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5”</td>
<td>41</td>
<td>60</td>
<td>51</td>
</tr>
<tr>
<td>1.75”</td>
<td>48</td>
<td>70</td>
<td>59</td>
</tr>
<tr>
<td>2”</td>
<td>54</td>
<td>80</td>
<td>67</td>
</tr>
<tr>
<td>2.25”</td>
<td>60</td>
<td>85</td>
<td>73</td>
</tr>
<tr>
<td>2.5”</td>
<td>68</td>
<td>95</td>
<td>81</td>
</tr>
<tr>
<td>2.75”</td>
<td>74</td>
<td>105</td>
<td>89</td>
</tr>
<tr>
<td>3”</td>
<td>81</td>
<td>110</td>
<td>96</td>
</tr>
<tr>
<td>3.25”</td>
<td>88</td>
<td>120</td>
<td>104</td>
</tr>
<tr>
<td>3.5”</td>
<td>94</td>
<td>130</td>
<td>112</td>
</tr>
</tbody>
</table>

(Dimensions 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 \( \rightarrow A \) (possibly using a swivel plate \( \rightarrow B \))
- bolted waling \( \rightarrow A \)
- several sheet piles anchored together, as a unit \( \rightarrow C \) (possibly using a swivel plate \( \rightarrow D \))

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

![Anchorage without waling](image)

Bearing plate check cases \( A \) & \( B \): no waling, or waling with bolts

\[
F_{rd,pl} \leq F_{rd,pl} = \frac{4}{3} \left( h_a - \phi \right) \cdot X \cdot \left[ \sqrt{1 + \frac{2 \cdot \left( \frac{t_v}{X} \right)^2}{Y_{M0}}} - 1 \right] \cdot \frac{f_s}{Y_{M0}}
\]

<table>
<thead>
<tr>
<th>Case</th>
<th>Expression</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A with nut</td>
<td>( X = h_a - d^* )</td>
<td></td>
</tr>
<tr>
<td>B with swivel plate</td>
<td>( X = h_a )</td>
<td>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.</td>
</tr>
</tbody>
</table>
Bolt and anchor forces to be considered

Anchors with bolted waling

Bearing plate check cases: 

**C** & **D**: anchorage of several double piles (n>1)

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

- **C** with nut: \( X = \frac{h_s - d' + 2(n-1)(s-d')}{2n-1} \)
- **D** with swivel plate: \( X = \frac{h_s + 2(n-1)s}{2n-1} \)

where:
- for **A** & **B**: \( F_{bs} = \) horizontal component of the anchor force per double pile
- for **C** & **D**: \( F_{bs} = \) horizontal component of the anchor force per tie rod
- \( b_s, h_s, t_s = \) 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)
- \( \phi = \) 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):
  \[ F_{Ed} \leq \frac{\pi}{2\sqrt{2}} \left( \frac{d_{SW}^2 - \phi^2}{2} \right) \frac{f_y}{\gamma_{M0}} \]

- für **B** & **D** (with swivel plate):
  \[ F_{Ed} \leq d_s \left( \frac{h_s}{X} - \phi \right) \frac{f_y}{\gamma_{M0}} \]

where:
- \( d_s = \) diameter of semi-cylindrical lugs (= 50 mm [3])
- \( b_s = \) min \( \{b_s; b_i\} \)
- \( b_i = \) width of swivel plate
Eccentricity factor $\alpha_{ek,i}$ at anchor point “i”

NB:  
• If there is more than one level of anchors, $\alpha_{ek}$ 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.

$$\alpha_{ek,i} = \frac{1}{1 + \frac{C_{Sym,i}}{C_{Art}}}$$

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

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

$$C_{Sym,i} = k_{s,i} \cdot L_i \cdot 2$$

for: $\frac{h_{d,i}}{L_i} \geq 1.00$

Anchor levels to be considered

where:  
$\alpha_{ek,i}$ = 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]  
$C_{Art}$ = torsional stiffness of sheet pile [MN/m²] (from Tab. 3)  
$Ei$ = flexural stiffness of sheet pile wall [MN/m/m] (from Tab. 3)  
$k_{s,i}$ = modulus of soil reaction at the anchor point in question
(average over length 2L) [MN/m²] (cf guideline values in Tab. 2)

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

<table>
<thead>
<tr>
<th>Ground type</th>
<th>$k_s$ [MN/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat</td>
<td>2</td>
</tr>
<tr>
<td>Clay, silty clay, sandy/silty clay</td>
<td>5</td>
</tr>
<tr>
<td>Silt</td>
<td>10</td>
</tr>
<tr>
<td>Sand loose, moderately compact, compact</td>
<td>40, 80, 150</td>
</tr>
<tr>
<td>Gravel</td>
<td>100</td>
</tr>
</tbody>
</table>

NB:  
• If the soil is stratified, a mean value for $k_s$ at the anchor level must be found.
## Design parameters for AZ sheet piles with off-centre anchors

<table>
<thead>
<tr>
<th>Sheet piles</th>
<th>Flange width $b_f$ mm</th>
<th>Plate width $b_r$ mm</th>
<th>$E_I$ MN/m²</th>
<th>$C_{ax}$ MN/m²</th>
<th>Double pile width $B$ m</th>
<th>Flange thickness $t_f$ mm</th>
<th>Web thickness $tw$ mm</th>
<th>$t_{wr}$ cm/m</th>
<th>Interlock characteristic $K_e$ mm</th>
<th>$C_a$ mm</th>
<th>$W_{pl}$ cm²/m</th>
<th>$W_{sl}$ cm²/m</th>
<th>$A_e$ cm²/m</th>
<th>$\alpha$ [°]</th>
<th>$L_{cr}$ m</th>
<th>Classification as per EN 1993-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ 12</td>
<td>154</td>
<td>145-150</td>
<td>38.1</td>
<td>31.0</td>
<td>1.34</td>
<td>8.5</td>
<td>8.5</td>
<td>1.269</td>
<td>1.90</td>
<td>1409</td>
<td>1200</td>
<td>36.2</td>
<td>45.4</td>
<td>5.5</td>
<td>2 3 3 3 3 3 3 3 3</td>
<td></td>
</tr>
<tr>
<td>AZ 13</td>
<td>41.4</td>
<td>39.5</td>
<td>1.38</td>
<td>2.38</td>
<td>1528</td>
<td>1300</td>
<td>40.3</td>
<td>44.4</td>
<td>2 2 2 2 2 2 2 2 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 14</td>
<td>44.7</td>
<td>50.9</td>
<td>1.567</td>
<td>2.90</td>
<td>1651</td>
<td>1400</td>
<td>44.4</td>
<td>2 2 2 2 2 2 2 2 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 17</td>
<td>66.3</td>
<td>38.3</td>
<td>1.349</td>
<td>2.68</td>
<td>1944</td>
<td>1665</td>
<td>48.8</td>
<td>2 2 2 2 2 2 2 3 3 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 18</td>
<td>71.8</td>
<td>48.3</td>
<td>1.508</td>
<td>3.34</td>
<td>2104</td>
<td>1800</td>
<td>54.4</td>
<td>2 2 2 2 2 2 2 3 3 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 19</td>
<td>77.7</td>
<td>62.8</td>
<td>1.667</td>
<td>4.08</td>
<td>2275</td>
<td>1940</td>
<td>60.0</td>
<td>2 2 2 2 2 2 2 3 3 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 25</td>
<td>109.7</td>
<td>82.6</td>
<td>1.778</td>
<td>4.58</td>
<td>2873</td>
<td>2455</td>
<td>71.5</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 26</td>
<td>116.6</td>
<td>106.5</td>
<td>1.937</td>
<td>5.38</td>
<td>3059</td>
<td>2600</td>
<td>77.7</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 28</td>
<td>123.8</td>
<td>120.6</td>
<td>2.095</td>
<td>6.24</td>
<td>3252</td>
<td>2755</td>
<td>83.8</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 34</td>
<td>165.3</td>
<td>130.5</td>
<td>2.063</td>
<td>8.57</td>
<td>3980</td>
<td>3430</td>
<td>87.7</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 36</td>
<td>173.9</td>
<td>153.1</td>
<td>2.222</td>
<td>9.60</td>
<td>4196</td>
<td>3600</td>
<td>94.2</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 38</td>
<td>182.9</td>
<td>181.0</td>
<td>2.381</td>
<td>10.70</td>
<td>4417</td>
<td>3780</td>
<td>100.7</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 36 n</td>
<td>188.5</td>
<td>62.9</td>
<td>1.600</td>
<td>7.22</td>
<td>4098</td>
<td>3597</td>
<td>74.4</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 38 n</td>
<td>199.2</td>
<td>76.7</td>
<td>1.743</td>
<td>8.10</td>
<td>4353</td>
<td>3793</td>
<td>80.9</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 40 n</td>
<td>209.9</td>
<td>91.4</td>
<td>1.886</td>
<td>9.02</td>
<td>4614</td>
<td>3989</td>
<td>87.3</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 46</td>
<td>231.9</td>
<td>221.4</td>
<td>2.414</td>
<td>10.39</td>
<td>5295</td>
<td>4595</td>
<td>107.4</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 48</td>
<td>242.9</td>
<td>248.6</td>
<td>2.586</td>
<td>11.58</td>
<td>5553</td>
<td>4800</td>
<td>114.8</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ 50</td>
<td>254.2</td>
<td>285.2</td>
<td>2.759</td>
<td>12.83</td>
<td>5816</td>
<td>5015</td>
<td>122.2</td>
<td>2 2 2 2 2 2 2 2 2 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

\[
F_{E,i} \leq R_{k,i,Ex,AZ} = \min \left( R_{L,z,k,k} ; R_{yf,k,k} ; R_{W,k,k} \right) \frac{\gamma_{Fr}}{\gamma_{Mo}} \]

where:

\[
R_{yf,k,k} = (h_y + t_y) \cdot t_y \cdot f_y \cdot \left( 1 + \alpha_{c,i} \right) \]

- punching shear resistance of flange

\[
R_{W,k,k} = h_y \cdot t_W \cdot f_y \cdot \left( 1 + \alpha_{c,i} \right) \]

- tensile resistance of web

\[
R_{L,z,k,k} = (h_y + 2h_y) \cdot R_L \cdot f_y \cdot \frac{1}{1 - \alpha_{c,i}} \]

- interlock resistance

\[
\text{NB: For the interlock resistance } R_{L,z,k,k} \text{ take } f_y. \]

\[
\text{ultimate tensile strength of AZ sheet piles (from Tab. 4)}
\]

\[
\alpha_{c,i} = \text{eccentricity factor at anchor point concerned}
\]

In the expressions above:

- \( F_{E,i} \) = anchor force applied, per double pile

- \( F'_{E,i} = \) anchor force applied (horizontal component) (per linear metre)

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

- \( K_a = \) interlock characteristic coefficient (from Tab. 3)

- \( t_x \) = flange thickness / web thickness (from Tab. 3)

- \( b_y \) = width / length of bearing plate

- \( f_y, f_c = \) yield strength / ultimate tensile strength of AZ sheet piles (from Tab. 4)

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

\[
\text{NB: For } F_{E,i} \text{ take the horizontal component of the anchor force introduced into the double pile (cf diagram on page 7).}
\]

\[
\text{Note: The expressions above, especially } K_a, \text{ are derived from equations (5.23), (5.24), and (5.25) in document [1].}
\]

**Reduction coefficients \( \beta_{c,i} \) at anchor point “i”**

At the anchor point “i” considered:

\[
\beta_{c,i} = \frac{1 - (1 - \alpha_{c,i}) \cdot F_{E,i}}{C_{ex} \cdot f_y}
\]

where:

- \( \beta_{c,i} = \) reduction coefficient at anchor point “i”

- \( \alpha_{c,i} = \) eccentricity factor at anchor point “i”

- \( F_{E,i} = \) 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, \( \beta_{c,i} \) must be determined separately for each level.

\[
\text{Note: In the case of retaining walls combining off-centre anchors and centred anchors or braces, take } \beta_{c} = 1.0 \text{ at centred anchor or bracing points.}
\]
Check of bending moment and shear capacity of sheet piling at anchor point

Classes 1 and 2:

\[ M_{EJ} \leq M_{c,Kd} = \beta_{ax,J} \cdot W_{pl,Net} \cdot \frac{f_y}{\gamma_{M0}} \]

\[ W_{pl,Net} = W_{pl,GE} \cdot r_{Wpl} \]

\[ r_{Wpl} = 1.0 - 0.8 \cdot \phi \]

Class 3:

\[ M_{EJ} \leq M_{c,Kd} = \beta_{ax,J} \cdot W_{cl,Net} \cdot \frac{f_y}{\gamma_{M0}} \]

\[ W_{cl,Net} = W_{cl,GE} \cdot r_{Wcl} \]

\[ r_{Wcl} = 1.0 - 1.3 \cdot \phi \]

and:

\[ V_{EJ} \leq V_{kd} = \beta_{ax,J} \cdot A_{w} \cdot \frac{f_y}{\sqrt{3} \cdot \gamma_{M0}} \]

and also, for: \( \frac{V_{EJ}}{V_{kd}} > 0.50 \): M-V interaction:

\[ M_{EJ} \leq M_{V,Kd} = \beta_{ax,J} \cdot \left( W_{pl,Net} - \frac{\rho \cdot A_{w}^2}{4 t_{w} \cdot \sin \alpha} \right) \cdot \frac{f_y}{\gamma_{M0}} \]

where: \( \rho = \left( \frac{2 V_{EJ}}{V_{kd}} - 1 \right)^2 \)

In the expressions above:

- \( M_{EJ} \) = bending moment in cross-section considered [kNm/m]
- \( V_{EJ} \) = shear force in cross-section considered [kN/m]
- \( W_{pl}, W_{el} \) = elastic/plastic section modulus of AZ sheet pile [cm³/m] (from Tab. 3)
- \( A_{w} \) = shear area of AZ sheet pile [cm²/m] (from Tab. 3)
- \( \alpha \) = 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
- \( \phi \) = diameter of hole in AZ sheet pile [m]
- \( \beta_{ax,A} \) = 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:
\[
M_{SI} \leq M_{z,kd} = \beta_{ex,F} \cdot W_{fl} \cdot \frac{f_y}{\gamma_{M0}}
\]

Class 3:
\[
M_{SI} \leq M_{z,kd} = \beta_{ex,F} \cdot W_{df} \cdot \frac{f_y}{\gamma_{M0}}
\]

and:
\[
V_{SI} \leq V_{k,j} = \beta_{ex,F} \cdot \frac{A_V}{\sqrt{3}} \cdot \frac{f_y}{\gamma_{M0}}
\]

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 \( \beta_{ex,r} \). More favourable values can be determined as explained below.

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

More favourable reduction coefficients, \( \beta_{ex,r} \), can be determined for general sections by taking account of: the distance between the anchor point and the section considered; where applicable, the distance \( L_s \) 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 \( x \geq \frac{L_{Ex}}{2} \) : \( \beta_{ex,F} = 1,0 \)

maximum moment for \( x < \frac{L_{Ex}}{2} \) : interpolation between \( \beta_{ex,1} \) and \( \beta_{ex,F} = 1,0 \)

where: \( x \) = distance between anchor point and section with maximum moment (in general section)
\( L_s \) = reference length of sheet pile (from Tab. 3)

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

\[
L_A \geq L_{Ex}
\]

maximum moment for \( x_i \leq \frac{L_s}{2} \) - 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 \( x_i \leq \frac{L_s}{2} \) - zone (3): linear interpolation between \( \beta_{ex,2} \) & \( \beta_{ex,F} = 1,0 \)

where: \( L_s \) = distance between the two adjacent layers of anchors

A) Extreme case (large distance):

maximum moment for \( x_i \leq \frac{L_s}{2} \) - 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 \( x_i \leq \frac{L_s}{2} \) - zone (3): linear interpolation between \( \beta_{ex,2} \) & \( \beta_{ex,F} = 1,0 \)
B) Normal case:
\[ L_{E_{x}} \geq L_{d} \geq L_{E_{x}} / 2 \]

maximum moment for \( x_{1} \leq L_{A} - L_{E_{x}} / 2 \) - zone (1):
linear interpolation between
\[ \beta_{e_{1.1}} \& \beta_{F.1} = \beta_{e_{1.1}} + (1 - \beta_{e_{1.1}}) \cdot \left( \frac{2 \cdot L_{d}}{L_{E_{x}}} - 1 \right) \]

maximum moment in zone (2):
linear interpolation between \( \beta_{e_{1,2}} \) & \( \beta_{e_{2,2}} \)
linear interpolation between
\[ \beta_{e_{1.2}} + \beta_{F.2} = \beta_{e_{2.2}} + (1 - \beta_{e_{2.2}}) \cdot \left( \frac{2 \cdot L_{d}}{L_{E_{x}}} - 1 \right) \]

maximum moment for \( x_{2} \leq L_{A} - L_{E_{x}} / 2 \) - zone (3):
linear interpolation between \( \beta_{e_{1,1}} \) & \( \beta_{e_{2,2}} \)

C) Extreme case (short distance):
\[ L_{d} < L_{E_{x}} / 2 \]
linear interpolation between \( \beta_{e_{1,1}} \) & \( \beta_{e_{2,2}} \)
Example of design

System and action effects

\begin{itemize}
  \item It is proposed to anchor every second double pile.
  \item It is proposed to install horizontal tie rods: smooth bars with threaded upset ends, with swivel plate to cater for possible settlements.
  \item Intermediate double sheet piles will be bolted to a waling consisting of two 300 mm channel sections set 160 mm apart.
\end{itemize}

Choice of bolt, tie rod, and bearing plate dimensions

\begin{itemize}
  \item Waling: \( F_{sw} = 1.26 \times 366 = 461 \text{ kN} \) / double pile
    choice: bolt \( d_s = 2.25" \) (no calculation)
    choice: plate \( b_s / h_s / t_s = 140 / 220 / 40 \text{ mm} / \text{S355JR} \)
  \item Anchor: \( F_{sw} = 2 \times 1.26 \times 366 = 922 \text{ kN} \) / double pile
    choice: tie rod \( d_s = 3.0" \) (no calculation)
    choice: plate \( b_s / h_s / t_s = 140 / 220 / 85 \text{ mm} / \text{S355JR} \)
\end{itemize}

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

\[ b_2 = 140 \text{ mm} \leq b_2 = 143 \text{ mm} \]
\[ 0.90 \cdot b_2 = 129 \text{ mm} \]
\[ h_2 = 220 \text{ mm} \leq 2.5 \cdot h_2 = 350 \text{ mm} \]
\[ \geq 2 \cdot t_F = 36 \text{ mm} \]

Bolt bearing plates:
\[ t_a = 40 \text{ mm} \geq \min t_a = 40 \text{ mm} \]
\[ \geq d_a / 3 = 19 \text{ mm} \]

Tie rod bearing plates:
\[ t_a = 85 \text{ mm} \geq \min t_a = 40 \text{ mm} \]
\[ \geq d_a / 3 = 25 \text{ mm} \]

where: \( \gamma_{Mo} = 1.0 \)

Check of bolt bearing plate in bending

With: \( d_a = 2.25'' \) \( \phi = 60 \text{ mm} \) \( d' = 73 \text{ mm} \)
and (type A):
\[ X = h_2 - d' = 220 - 73 = 147 \text{ mm} \]
\[ F_{EL} \leq F_{EL,pl} = \frac{4}{3} \left( t_a - \phi \right) X \cdot \frac{1}{1 + 3 \left( t_a - \phi \right) / X} - 1 \]
\[ \frac{f_c}{E_M} = \frac{4}{3} (140 - 60) \cdot 147 \cdot \frac{1}{1 + 3 \left( 147 / 40 \right)} - 1 \]
\[ = 355 \text{ kN} \leq 461 \text{ kN} \]

Additional check:
\[ F_{EL} \leq \frac{\pi}{2 \sqrt{2}} (t_{aw} - \phi) \frac{f_c}{E_M} = \frac{\pi}{2 \sqrt{2}} (85^2 - 60^2) \cdot \frac{355}{1000-1.0} = 1429 \text{ kN} > 461 \text{ kN} \]

Check of tie rod bearing plate in bending

With: \( n = 2 \) \( s = 160 \text{ mm} \)
\[ d_a = 3.0'' \] \( \phi = 81 \text{ mm} \)
and (type D):
\[ X = \frac{h_2 + 2(n-1)s}{2n-1} = \frac{220 + 2 \cdot 1 \cdot 160}{3} = 180 \text{ mm} \]
\[ F_{EL} \leq F_{EL,pl} = \frac{4}{3n} \left( t_a - \phi \right) X \cdot \frac{1}{1 + 3 \left( t_a - \phi \right) / X} - 1 \]
\[ \frac{f_c}{E_M} = \frac{4}{3} (140 - 81) \cdot 180 \cdot \frac{1}{1 + 3 \left( 180 / 85 \right)} - 1 \]
\[ = 355 \text{ kN} \leq 978 \text{ kN} > 922 \text{ kN} \]

Additional check:
\[ F_{EL} \leq d_a \left( t_a - \phi \right) \frac{f_c}{E_M} = 50 \cdot (140 - 81) \cdot \frac{355}{1000-1.0} = 1047 \text{ kN} > 922 \text{ kN} \]
Determination of eccentricity factor

AZ-Profil: \( AZ36 \rightarrow \)
\[
EI = 173,88 \text{ MNm}^2 / \text{m} \\
C_{Art} = 153,15 \text{ MN} / \text{m}^2
\]

Ground at anchor level: moderately compact sand \( \rightarrow \)
\( k_s = 80 \text{ MN} / \text{m}^3 \)

Anchor level: \( h_j = 3,0 \text{ m} \)
\[
L_i = \sqrt{\frac{4EI}{k_s}} = 1,72 \text{ m} \\
\Rightarrow \frac{h_j}{L_i} = 1,75 \geq 1,00 \\
\Rightarrow C_{20m} = k_sL_i \cdot 2 = 275 \text{ MN} / \text{m}^2 \\
\Rightarrow \alpha_s = \frac{1}{1 + \frac{C_{20m}}{C_{Art}}} = 0,36
\]

Check of the resistance of the AZ36 pile to local forces

\[
R_{L,i,k,b} = (h_j + 2b_j) \cdot f_y \cdot \frac{1}{1-\alpha_s} = (220 + 2 \cdot 140) \cdot 2,37 \cdot \frac{410}{1000} \cdot \frac{1}{1-0,36} = 759 \text{ kN}
\]

\[
R_{ty,b} = (h_j + b_j) \cdot t_y \cdot \frac{f_y}{\sqrt{3}} \cdot (1+\alpha_s) = (220 + 140) \cdot 18 \cdot \frac{270}{1000 \sqrt{3}} \cdot (1+0,36) = 1374 \text{ kN}
\]

\[
R_{sv,b} = h_j \cdot t_y \cdot f_y \cdot (1+\alpha_s) = 220 \cdot 14 \cdot \frac{270}{1000} \cdot (1+0,36) = 1131 \text{ kN}
\]

\( \Rightarrow F_{El} = 461 \text{ kN} \leq R_{R,i,k,b} = \frac{\min(R_{L,i,k,b}; R_{ty,b}; R_{sv,b})}{\gamma_{M0}} = \frac{759}{1,0} = 759 \text{ kN} \)

Note: This check is valid for bearing plates for both bolts and anchors since their dimensions \( b \) and \( h_j \) are the same.

Reduction coefficient \( \beta_{ex} \) at anchor point

\[
\beta_{ex} = \frac{1}{\sqrt{1 - (1-\alpha_s) \frac{F_{El}}{C_{Ex} \cdot f_y}}} = \sqrt{1 - (1-0,36) \frac{366}{9,60 \cdot 355}} = 0,96
\]

Check of action effects at anchor point

AZ sheet pile: \( AZ36 / S270GP \rightarrow W_{el} = 3600 \text{ cm}^3 / \text{m} \rightarrow A_p = 94,2 \text{ cm}^2 / \text{m} \)

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: \( \Phi = 81 \text{ mm} \) (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).

\[
W_{el,Nel} = W_{el,\Phi,\Lambda} \cdot r_{W,el} = 3600 \cdot (1,0 - 1,3 \cdot 0,081) = 3221 \text{ cm}^3 / \text{m}
\]

\[
M_{El} \leq M_{c,b,b} = \beta_{ex,b} \cdot W_{el,Nel} \cdot \frac{f_y}{\gamma_{M0}} = 0,96 \cdot 3221 \cdot \frac{270}{1000 \cdot 1,0} = 835 \text{ kNm} / \text{m} > 129 \text{ kNm/m} \checkmark
\]

\[
V_{El} \leq V_{k,b} = \beta_{ex,b} \cdot \frac{A_p \cdot f_y}{\sqrt{3} \cdot \gamma_{M0}} = 0,96 \cdot \frac{94,2}{\sqrt{3}} \cdot \frac{270}{10 \cdot 1,0} = 1410 \text{ kN/m} > 280 \text{ kN/m} \checkmark \quad \frac{V_{El}}{V_{k,b}} = 0,20 \leq 0,50 \checkmark
\]

15
Check of action effects in general sections

To simplify matters (with $\beta_{ex, r} = \beta_{ex, l}$):

$$M_{c,r,d} = \beta_{cr} \cdot W_{sf} \cdot f_{y} \cdot \frac{270}{\gamma_{M0}} = 0,96 \cdot 3600 \cdot \frac{270}{1000 \cdot 1,0} = 933 \text{ kNm/m} < M_{EJ} = 965 \text{ kNm/m}$$

With a more precise value for $\beta_{ex, r}$:

$x = 6,60 \text{m}$ (distance between tie rod and section with maximum moment):

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

$$M_{EJ} \leq M_{c,r,d} = \beta_{cr} \cdot W_{sf} \cdot f_{y} \cdot \frac{270}{\gamma_{M0}} = 972 \text{ kNm/m} > 965 \text{ kNm/m}$$

Note: With $\beta_{ex, r} = \beta_{ex, l}$ and taking the plastic moment resistance, the check would also be met:

$$M_{Ed} \leq M_{Ed, r} = 1088 \text{ kNm/m} > 965 \text{ kNm/m}.$$

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

System diagram

### Bibliography


[4] Steel Sheet Piling General Catalogue

[5] EAB, Empfehlungen Arbeitsausschuss Baugruben


Off-centre anchoring of AZ sheet pile walls

Steel Sheet Piling