Design situation
Consider a sheet pile wall that retains $H_{\text{nom}} = 8.0\text{m}$ of dense sand with characteristic weight density $\gamma_k = 20\frac{\text{kN}}{\text{m}^3}$ and drained angle of shearing resistance $\varphi_k = 38^\circ$. The ground behind the wall is horizontal and subject to a blanket surcharge (representing traffic loading) - but, for simplicity, we will assume $q_k = 0\text{kPa}$. The ground is dry.

The sheet pile is a Z section with flange thickness $t_f = 8.5\text{mm}$, web thickness $t_w = 8.5\text{mm}$, web height $h = 302\text{mm}$, clutch-to-clutch breadth $b = 670\text{mm}$, elastic section modulus $W_{\text{el}} = 1400\frac{\text{cm}^3}{\text{m}}$, and characteristic yield strength $f_{\text{yk}} = 355\text{MPa}$.

An anchor with ultimate design resistance of $R_{a,d} = 130\frac{\text{kN}}{\text{m}}$ will be installed at an angle $\theta = 30^\circ$ to the horizontal to stabilize the wall.

Geometry
Allowing for an unplanned excavation in ULS verifications, the design retained height of the wall is:

$$H_d = H_{\text{nom}} + \min\{10\% \times H_{\text{nom}} \times 0.5\text{m}\} = 8.5\text{m}$$

Material properties
Partial factors from Set $\left[\begin{array}{c} M1 \\ M2 \end{array}\right]$: $\gamma_\varphi = \left[\begin{array}{c} 1 \\ 1.25 \end{array}\right]$

Design angle of shearing resistance:
\[
\varphi_d = \tan\left(\frac{\tan(\varphi_k)}{\gamma_d}\right) = 38.0 \degree
\]

Characteristic value of soil’s constant-volume angle of shearing resistance is assumed to be:

\[\varphi_{cv,k} = 30^\circ\]

Design value of soil’s constant-volume angle of shearing resistance is:

\[\varphi_{cv,d} = \min(\varphi_d, \varphi_{cv,k}) = 30^\circ\]

Angle of wall friction is \(k = 0.67\) times the soil’s constant-volume angle of shearing resistance:

\[\delta_d = k \varphi_{cv,d} = 20^\circ\]

Earth pressure coefficients from Annex C of EN 1997-1:

\[
\begin{bmatrix}
K_{a,h} & K_{p,h}
\end{bmatrix} = \begin{bmatrix}
0.21 & 7.39
0.26 & 5.18
\end{bmatrix}
\]

**Actions**

Partial factors from Set \(A1, A2\):

\[
\gamma = \begin{bmatrix}
1.35 & 1.5
1 & 1.3
\end{bmatrix}, \quad \gamma_{G,fav} = 1 \quad \text{and} \quad \gamma_Q = \begin{bmatrix}
1.35 & 1
\end{bmatrix}
\]

'Single source principle' allows \(\gamma_{G,fav} = \gamma_G = \begin{bmatrix}
1.35
1
\end{bmatrix}\)

Ratio of variable and permanent partial factors is:

\[
\frac{\gamma Q}{\gamma G} = \begin{bmatrix}
1.11
1.3
\end{bmatrix}
\]

Assume a depth of embedment \(d = 1.38\) m

Overturning moment about anchor is:

\[
M_{Ed,dst} = \left[ \gamma G K_{a,h} \left( \frac{1}{3} \gamma_k \left( H_d + d \right)^3 + \frac{1}{2} \gamma Q / G \times q_k \times \left( H_d + d \right)^2 \right) \right] = \begin{bmatrix}
1790 \ kN\cdot m
2040 \ kN\cdot m
\end{bmatrix}
\]

Restoring moment about anchor is:

\[
M_{Ed,stab} = \left[ \gamma_{G,fav} K_{p,h} \left( \frac{1}{2} \gamma_k \times d^2 \times \left( H_d + \frac{2}{3} d \right) \right) \right] = \begin{bmatrix}
1789 \ kN\cdot m
2061 \ kN\cdot m
\end{bmatrix}
\]

Out of balance moment is:

\[
\frac{M_{Ed,dst} - M_{Ed,stab}}{M_{Ed,stab}} = \begin{bmatrix}
0.1
-1
\end{bmatrix} \% 
\]

Active thrust on retained side of wall is:

\[
P_{a,Ed} = \left[ \gamma G K_{a,h} \left( \frac{1}{2} \gamma_k \left( H_d + d \right)^2 + \gamma Q / G \times q_k \times \left( H_d + d \right) \right) \right] = \begin{bmatrix}
272 \ kN
291 \ kN
\end{bmatrix}
\]

Passive thrust on restraining side of wall is:

\[
P_{p,Ed} = \left[ \gamma_{G,fav} K_{p,h} \left( \frac{1}{2} \gamma_k \times d^2 \right) \right] = \begin{bmatrix}
190 \ kN
209 \ kN
\end{bmatrix}
\]

Hence net thrust is:

\[
P_{Ed} = P_{a,Ed} - P_{p,Ed} = \begin{bmatrix}
81.9 \ kN
81.7 \ kN
\end{bmatrix}
\]

Hence axial force transferred to the anchor is:
The depth of zero shear force in the retaining wall can be found (approximately) from:

\[ z = \frac{P_{Ed}}{\gamma G K_{a,h} \times \frac{1}{2} \gamma k} = \begin{pmatrix} 5.42 \\ 5.57 \end{pmatrix} \text{ m} \]

... and checked for accuracy using:

\[ V_{z,Ed} = P_{Ed} - \left[ \gamma G K_{a,h} \times \left( \frac{1}{2} \gamma k \times z^2 + \frac{1}{2} Q/G \times q_k \times z \right) \right] = \begin{pmatrix} 0.0 \\ 0.0 \end{pmatrix} \text{ kN/m} \]

Hence the maximum bending moment in the wall is:

\[ M_{Ed} = \left[ P_{Ed} z - \gamma G K_{a,h} \times \left( \frac{1}{6} \gamma k \times z^3 + \frac{1}{2} Q/G \times q_k \times z \right) \right] = \begin{pmatrix} 296 \\ 303 \end{pmatrix} \text{ kNm/m} \]

Maximum bending moment from either combination is:

\[ M_{Ed} = \max\left( M_{Ed_1}, M_{Ed_2} \right) = 303 \text{ kNm/m} \]

Maximum shear force in the wall is:

\[ V_{Ed} = \max\left( V_{Ed_1}, V_{Ed_2} \right) = 81.9 \text{ kN/m} \]

**Verifications**

**Verification of resistance to overturning**

'Degree of utilization' \( \Lambda = \frac{M_{Ed, dst}}{M_{Ed, stb}} = \begin{pmatrix} 100 \\ 99 \end{pmatrix} \) % or 'Overdesign factor' \( \text{ODF} = \frac{M_{Ed, stb}}{M_{Ed, dst}} = \begin{pmatrix} 1 \\ 1.01 \end{pmatrix} \)

The design is unacceptable if the degree of utilization is > 100% (or overdesign factor is < 1)

**Verification of bending resistance**

Partial factor on yield strength of steel is \( \gamma_{M0} = 1.0 \) (from EN 1993-1-1)

Factor for reduced shear force in interlocks \( \beta_B = 1.0 \)

Design bending resistance of sheet pile section is:

\[ M_{c,Rd} = \frac{\beta_B W_{el} f_{yk}}{\gamma_{M0}} = 497 \text{ kNm/m} \]

'Degree of utilization' \( \Lambda = \frac{M_{Ed}}{M_{c,Rd}} = 61 \) % or 'Overdesign factor' \( \text{ODF} = \frac{M_{c,Rd}}{M_{Ed}} = 1.64 \)

The design is unacceptable if the degree of utilization is > 100% (or overdesign factor is < 1)

**Verification of shear resistance**

Projected shear area is:

\[ A_v = \frac{t_w (h - t_f)}{b} = 3724 \text{ mm}^2 \text{ mm} \]

Design shear resistance of sheet pile section is:

\[ V_{pl,Rd} = \frac{A_v f_{yk}}{\sqrt{3} \gamma_{M0}} = 763.2 \text{ kN/m} \]
'Degree of utilization' \( \Lambda = \frac{V_{Ed}}{V_{pl,Rd}} = 11\% \) or 'Overdesign factor' \( \text{ODF} = \frac{V_{pl,Rd}}{V_{Ed}} = 9.3 \)

The design is unacceptable if the degree of utilization is > 100% (or overdesign factor is < 1)

**Verification of resistance to anchor pull-out**

Design pull-out resistance of anchor is: \( F_{a,Rd} = R_{a,d} = 130 \frac{kN}{m} \)

'Degree of utilization' \( \Lambda = \frac{F_{a,Ed}}{F_{a,Rd}} = 73\% \) or 'Overdesign factor' \( \text{ODF} = \frac{F_{a,Rd}}{F_{a,Ed}} = 1.37 \)

The design is unacceptable if the degree of utilization is > 100% (or overdesign factor is < 1)