

Example 12.1-DA3
Embedded cantilever wall
Verification of strength (limit state GEO)

Design situation

Consider an embedded sheet pile retaining wall which is retaining $H_{nom} = 4\text{m}$ of medium dense sand overlying low/medium strength clay. A characteristic variable surcharge $q_{Qk} = 10\text{kPa}$ acts at the head of the wall. The sand has

characteristic weight density $\gamma_{k1} = 18 \frac{\text{kN}}{\text{m}^3}$, angle of shearing resistance

$\varphi_k = 36^\circ$, and effective cohesion $c'_{k1} = 0\text{kPa}$. Its angle of shearing resistance under constant volume conditions is estimated to be $\varphi_{cv,k} = 32^\circ$.

The clay has characteristic weight density $\gamma_{k2} = 20 \frac{\text{kN}}{\text{m}^3}$ and undrained

strength $c_{u,k} = 40\text{kPa}$. The wall toe is at a nominal depth $d_{nom} = 9.8\text{m}$ below formational level. The ground is dry throughout.

Design Approach 3

Geometry

Unplanned 'overdig' $\Delta H = \min(10\% \times H_{nom}, 0.5\text{m}) = 0.4\text{m}$

Unplanned height of excavation $H_d = H_{nom} + \Delta H = 4.4\text{m}$

Reduced depth of embedment $d_d = d_{nom} - \Delta H = 9.4\text{m}$

For cantilever walls, earth pressures below the effective wall toe (point O) can be replaced by an equivalent reaction R. The design embedment depth is

conservatively calculated as: $d_{O,d} = \frac{d_d}{1.2} = 7.83\text{m}$ and the nominal

embedment depth as $d_{O,nom} = d_{O,d} + \Delta H = 8.23\text{m}$

Actions

Vertical total stresses on retained side of wall (from soil self-weight only):

at top of sand $\sigma_{v,k1} = 0\text{kPa}$

at bottom of sand $\sigma_{v,k2} = \gamma_{k1} \times H_{nom} = 72\text{kPa}$

at top of clay $\sigma_{v,k3} = \sigma_{v,k2} = 72\text{kPa}$

$$\text{at point 'O'} \quad \sigma_{v,k_4} = \sigma_{v,k_3} + (\gamma k_2 \times d_{O,nom}) = 236.7 \text{ kPa}$$

Vertical total stresses on restraining side of wall:

$$\text{at formation level } \sigma_{v,k_5} = 0 \text{ kPa}$$

$$\text{at point 'O'} \quad \sigma_{v,k_6} = \sigma_{v,k_5} + (\gamma k_2 \times d_{O,d}) = 156.7 \text{ kPa}$$

Material properties

Partial factors from Set M2: $\gamma_\varphi = 1.25$ and $\gamma_{cu} = 1.4$

$$\text{Design angle of shearing resistance of sand } \varphi_d = \tan^{-1} \left(\frac{\tan(\varphi_k)}{\gamma_\varphi} \right) = 30.2^\circ$$

Design constant volume angle of shearing resistance of sand

$$\varphi_{cv,d} = \tan^{-1} \left(\frac{\tan(\varphi_{cv,k})}{\gamma_\varphi} \right) = 26.6^\circ$$

For soil/steel interface, $k = \frac{2}{3}$

Design angle of wall friction $\delta_d = k \times \varphi_{cv,d} = 17.7 \text{ deg}$

Design undrained strength of clay $c_{u,d} = \frac{c_{u,k}}{\gamma_{cu}} = 28.6 \text{ kPa}$

Effects of actions

Partial factors from Set A2: $\gamma_G = 1$ and $\gamma_Q = 1.3$

Active earth pressure coefficients (sand) $K_{a\gamma} = 0.287$ $K_{aq} = 0.287$

Horizontal stresses on retained side of wall...

$$\sigma_{a,d_1} = \overrightarrow{(\gamma G \times K_{a\gamma} \times \sigma_{v,k_1} + \gamma Q \times K_{aq} \times q_{Qk})} = 3.7 \text{ kPa}$$

$$\sigma_{a,d_2} = \overrightarrow{(\gamma G \times K_{a\gamma} \times \sigma_{v,k_2} + \gamma Q \times K_{aq} \times q_{Qk})} = 24.4 \text{ kPa}$$

$$\sigma_{a,d_3} = \overrightarrow{[\gamma G \times (\sigma_{v,k_3} - 2 \times c_{u,d}) + \gamma Q \times q_{Qk}]} = 27.9 \text{ kPa}$$

$$\sigma_{a,d_4} = \overrightarrow{[\gamma G \times (\sigma_{v,k_4} - 2 \times c_{u,d}) + \gamma Q \times q_{Qk}]} = 192.5 \text{ kPa}$$

Horizontal stresses on restraining side of wall

$$\sigma_{p,d_5} = \overrightarrow{[\gamma G \times (\sigma_{v,k_5} + 2 \times c_{u,d})]} = 57.1 \text{ kPa}$$

$$\sigma_{p,d_6} = \left[\gamma_G \times \left(\sigma_{v,k_6} + 2 \times c_{u,d} \right) \right] = 213.8 \text{ kPa}$$

Horizontal thrust

$$\text{from sand } H_{Ed_1} = \left(\frac{\sigma_{a,d_1} + \sigma_{a,d_2}}{2} \right) \times H_{nom} = 56.3 \frac{\text{kN}}{\text{m}}$$

$$\text{from clay } H_{Ed_2} = \left[\left(\frac{\sigma_{a,d_3} + \sigma_{a,d_4}}{2} \right) \times d_{O,nom} \right] = 907.2 \frac{\text{kN}}{\text{m}}$$

$$\text{total } H_{Ed} = \sum_{i=1}^2 H_{Ed_i} = 963.6 \frac{\text{kN}}{\text{m}}$$

Overturning moments about point 'O' (subscripts refer to numbers on diagram)

$$M_{Ed_1} = \left[\frac{\sigma_{a,d_1}}{2} \times H_{nom} \times \left(\frac{2}{3} H_{nom} + d_{O,nom} \right) \right] = 81.4 \frac{\text{kNm}}{\text{m}}$$

$$M_{Ed_2} = \left[\frac{\sigma_{a,d_2}}{2} \times H_{nom} \times \left(\frac{1}{3} H_{nom} + d_{O,nom} \right) \right] = 467.3 \frac{\text{kNm}}{\text{m}}$$

$$M_{Ed_3} = \left(\frac{\sigma_{a,d_3}}{2} \times d_{O,nom} \times \frac{2}{3} d_{O,nom} \right) = 629.5 \frac{\text{kNm}}{\text{m}}$$

$$M_{Ed_4} = \left(\frac{\sigma_{a,d_4}}{2} \times d_{O,nom} \times \frac{1}{3} d_{O,nom} \right) = 2175.1 \frac{\text{kNm}}{\text{m}}$$

$$\text{total } M_{Ed} = \sum_{i=1}^4 M_{Ed_i} = 3353 \frac{\text{kNm}}{\text{m}}$$

Resistance

Partial factor from Set R1: $\gamma_{Re} = 1$

$$\text{Horizontal resistance } H_{Rd} = \left[\frac{\left(\frac{\sigma_{p,d_5} + \sigma_{p,d_6}}{2} \right) \times d_{O,d}}{\gamma_{Re}} \right] = 1061 \frac{\text{kN}}{\text{m}}$$

Restoring moment about point 'O' (subscripts refer to numbers on diagram)

$$M_{Rd_5} = \frac{\left(\frac{\sigma_{p,d_5}}{2} \times d_{O,d} \times \frac{2}{3} d_{O,d} \right)}{\gamma_{Re}} = 1169 \frac{\text{kNm}}{\text{m}}$$

$$M_{Rd_6} = \frac{\left(\frac{\sigma_{p,d_6}}{2} \times d_{O,d} \times \frac{1}{3} d_{O,d} \right)}{\gamma_{Re}} = 2187 \frac{\text{kNm}}{\text{m}}$$

$$\text{total } M_{Rd} = \sum_{i=5}^6 M_{Rd_i} = 3355 \frac{\text{kNm}}{\text{m}}$$

Verifications

Rotational equilibrium $M_{Ed} = 3353 \frac{\text{kNm}}{\text{m}}$ and $M_{Rd} = 3355 \frac{\text{kNm}}{\text{m}}$

Degree of utilization $\Lambda_{GEO,3} = \frac{M_{Ed}}{M_{Rd}} = 100\%$

Design is unacceptable if the degree of utilization is $> 100\%$

Reaction near wall toe $F_{Ed} = H_{Rd} - H_{Ed} = 97.7 \frac{\text{kN}}{\text{m}}$

Wall section must be designed for...

Maximum bending moment of $M_{d,max} = 222 \frac{\text{kNm}}{\text{m}}$

Maximum shear force of $V_{d,max} = 58.7 \frac{\text{kN}}{\text{m}}$