Example 12.1-DA2
Embedded cantilever wall
Verification of strength (limit state GEO)

Design situation

Consider an embedded sheet pile retaining wall which is retaining $H_{nom} = 4m$ of medium dense sand overlying low/medium strength clay. A characteristic variable surcharge $q_{Qk} = 10kPa$ acts at the head of the wall. The sand has characteristic weight density $\gamma_{k_1} = 18\frac{kN}{m^3}$, angle of shearing resistance $\varphi_k = 36°$, and effective cohesion $c'_k = 0kPa$. Its angle of shearing resistance under constant volume conditions is estimated to be $\varphi_{cv,k} = 32°$.

The clay has characteristic weight density $\gamma_{k_2} = 20\frac{kN}{m^3}$ and undrained strength $c_{u,k} = 40kPa$. The wall toe is at a nominal depth $d_{nom} = 9.8m$ below formational level. The ground is dry throughout.

Design Approach 2

Geometry

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

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

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

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: $d_{O,d} = \frac{d_d}{1.2} = 7.83\,m$ and the nominal embedment depth as $d_{O,nom} = d_{O,d} + \Delta H = 8.23\,m$

Actions

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

at top of sand $\sigma_{v,k_1} = 0kPa$

at bottom of sand $\sigma_{v,k_2} = \gamma_{k_1} \times H_{nom} = 72\,kPa$

at top of clay $\sigma_{v,k_3} = \sigma_{v,k_2} = 72\,kPa$

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

Vertical total stresses on restraining side of wall:

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

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

Material properties

Partial factors from Sets M1: $\gamma_\varphi = 1$ and $\gamma_{cu} = 1$

Design angle of shearing resistance of sand $\varphi_d = \tan^{-1}\left(\dfrac{\tan(\varphi_k)}{\gamma_\varphi}\right) = 36°$

Design constant volume angle of shearing resistance of sand

$$\varphi_{cv,d} = \tan^{-1}\left(\frac{\tan(\varphi_{cv,k})}{\gamma_\varphi}\right) = 32°$$

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

Design angle of wall friction $\delta_d = k \times \varphi_{cv,d} = 21.3\,\text{deg}$

Design undrained strength of clay $c_{u,d} = \dfrac{c_{u,k}}{\gamma_{cu}} = 40\,\text{kPa}$

Effects of actions

Partial factors from Set A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$

Active earth pressure coefficients (sand) $K_{a\gamma} = 0.222$ $K_{aq} = 0.222$

Horizontal stresses on retained side of wall...

$$\sigma_{a,d_1} = \overrightarrow{\left(\gamma_G \times K_{a\gamma} \times \sigma_{v,k_1} + \gamma_Q \times K_{aq} \times q_{Qk}\right)} = 3.3\,\text{kPa}$$

$$\sigma_{a,d_2} = \overrightarrow{\left(\gamma_G \times K_{a\gamma} \times \sigma_{v,k_2} + \gamma_Q \times K_{aq} \times q_{Qk}\right)} = 25\,\text{kPa}$$

$$\sigma_{a,d_3} = \overrightarrow{\left[\gamma_G \times \left(\sigma_{v,k_3} - 2 \times c_{u,d}\right) + \gamma_Q \times q_{Qk}\right]} = 4.2\,\text{kPa}$$

$$\sigma_{a,d_4} = \overrightarrow{\left[\gamma_G \times \left(\sigma_{v,k_4} - 2 \times c_{u,d}\right) + \gamma_Q \times q_{Qk}\right]} = 226.5\,\text{kPa}$$

Horizontal stresses on restraining side of wall

$$\sigma_{p,d_5} = \underrightarrow{\overrightarrow{\left(\sigma_{v,k_5} + 2 \times c_{u,d}\right)}} = 80\,\text{kPa}$$

$$\sigma_{p,d_6} = \left(\sigma_{v,k_6} + 2 \times c_{u,d}\right) = 236.7\,\text{kPa}$$

Horizontal thrust

from sand $$H_{Ed_1} = \left(\frac{\sigma_{a,d_1} + \sigma_{a,d_2}}{2}\right) \times H_{nom} = 56.6\,\frac{kN}{m}$$

from clay $$H_{Ed_2} = \overrightarrow{\left[\left(\frac{\sigma_{a,d_3} + \sigma_{a,d_4}}{2}\right) \times d_{O,nom}\right]} = 949.7\,\frac{kN}{m}$$

total $$H_{Ed} = \sum_{i=1}^{2} H_{Ed_i} = 1006.3\,\frac{kN}{m}$$

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

$$M_{Ed_1} = \overrightarrow{\left[\frac{\sigma_{a,d_1}}{2} \times H_{nom} \times \left(\frac{2}{3}H_{nom} + d_{O,nom}\right)\right]} = 72.7\,\frac{kNm}{m}$$

$$M_{Ed_2} = \overrightarrow{\left[\frac{\sigma_{a,d_2}}{2} \times H_{nom} \times \left(\frac{1}{3}H_{nom} + d_{O,nom}\right)\right]} = 477.5\,\frac{kNm}{m}$$

$$M_{Ed_3} = \overrightarrow{\left(\frac{\sigma_{a,d_3}}{2} \times d_{O,nom} \times \frac{2}{3}d_{O,nom}\right)} = 94.9\,\frac{kNm}{m}$$

$$M_{Ed_4} = \overrightarrow{\left(\frac{\sigma_{a,d_4}}{2} \times d_{O,nom} \times \frac{1}{3}d_{O,nom}\right)} = 2559\,\frac{kNm}{m}$$

total $$M_{Ed} = \sum_{i=1}^{4} M_{Ed_i} = 3204\,\frac{kNm}{m}$$

Resistance

Partial factor from Set R2: $\gamma_{Re} = 1.4$

Horizontal resistance $$H_{Rd} = \overrightarrow{\left[\frac{\left(\frac{\sigma_{p,d_5} + \sigma_{p,d_6}}{2}\right) \times d_{O,d}}{\gamma_{Re}}\right]} = 886\,\frac{kN}{m}$$

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

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

$$M_{Rd_6} = \overrightarrow{\left(\frac{\frac{\sigma_{p,d_6}}{2} \times d_{O,d} \times \frac{1}{3} d_{O,d}}{\gamma_{Re}}\right)} = 1729 \frac{kNm}{m}$$

$$\text{total } M_{Rd} = \sum_{i=5}^{6} M_{Rd_i} = 2898 \frac{kNm}{m}$$

Verifications

Rotational equilibrium $M_{Ed} = 3204 \frac{kNm}{m}$ and $M_{Rd} = 2898 \frac{kNm}{m}$

Desgree of utilization $\boxed{\Lambda_{GEO,2} = \frac{M_{Ed}}{M_{Rd}} = 111\,\%}$

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

Reaction near wall toe $F_{Ed} = H_{Rd} - H_{Ed} = -120.4 \frac{kN}{m}$