Example 11.3
T-shaped gravity wall retaining wet fill
Verification of drained strength (limit state GEO)

Design situation

Re-consider the design of the T-shaped gravity retaining wall from the previous worked example. Constraints during construction prevent a drain being placed at the heel of the wall. Therefore, the drain will be positioned behind the wall stem to reduce water level in the fill to a depth $d_w = 1.5\text{m}$ below the retained surface. The base of the wall is increased to $B = 4.3\text{m}$ wide but all other dimensions remain unchanged. Material properties are also unchanged.❶

Design Approach 1

Geometrical parameters

Unplanned excavation $\Delta H = \min(10\%\ H, 0.5\text{m}) = 0.3\,\text{m}$

Design retained height $H_d = H + \Delta H = 3.3\,\text{m}$

Width of heel $b = B - t_s - x = 3.55\,\text{m}$

Actions

Characteristic vertical actions and moments due to self-weight❷

Wall base: $W_{Gk_1} = \gamma_{ck} \times B \times t_b = 32.3\ \text{kN/m}$

Moment from base: $M_{k_1} = W_{Gk_1} \times \frac{B}{2} = 69.3\ \text{kNm/m}$

Wall stem: $W_{Gk_2} = \gamma_{ck} \times \left(H + d - t_b\right) \times t_s = 20\ \text{kN/m}$

Moment from stem: $M_{k_2} = W_{Gk_2} \times \left(\frac{t_s}{2} + x\right) = 12.5\ \text{kNm/m}$

Backfill: $W_{Gk_3} = \gamma_k \times b \times \left(H + d - t_b\right) = 204.5\ \text{kN/m}$

Moment from backfill: $M_{k_3} = W_{Gk_3} \times \left(\frac{b}{2} + t_s + x\right) = 516.3\ \text{kNm/m}$

Total characteristic self-weight $W_{Gk} = \sum W_{Gk} = 256.7\ \text{kN/m}$

Total characteristic stabilizing moment $M_{Ek,stb} = \sum M_k = 598.1\ \text{kNm/m}$

Characteristic surcharge (variable) $Q_{Qk} = q_{Qk} \times (B - x) = 38\ \text{kN/m}$

Soil stresses at depth of water table along virtual back of wall

vertical total stress $\sigma_{vk,w} = \gamma_k \times d_w = 27\ \text{kPa}$

pore pressure $u_w = 0\text{kPa}$

vertical effective stress $\sigma'_{vk,w} = \sigma_{vk,w} - u_w = 27\ \text{kPa}$ ❸

Soil stresses at wall heel

vertical total stress $\sigma_{vk,h} = \gamma_k \times (H + d) = 63\ \text{kPa}$

height of water table $h_w = H + d - d_w = 2\,\text{m}$

pore pressure $u_h = \gamma_w \times h_w = 19.6\ \text{kPa}$

vertical effective stress $\sigma'_{vk,h} = \sigma_{vk,h} - u_h = 43.4\ \text{kPa}$ ❸

Effects of actions

Partial factors, Sets $\begin{pmatrix} A1 \\ A2 \end{pmatrix}$: $\gamma_G = \begin{pmatrix} 1.35 \\ 1 \end{pmatrix}$, $\gamma_{G,fav} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$, and $\gamma_Q = \begin{pmatrix} 1.5 \\ 1.3 \end{pmatrix}$

Design vertical actions (unfavourable)

total $V_d = \gamma_G \times W_{Gk} + \gamma_Q \times Q_{Qk} = \begin{pmatrix} 403.6 \\ 306.1 \end{pmatrix} \dfrac{\text{kN}}{\text{m}}$

water upthrust $U_d = \gamma_G \times \dfrac{u_h}{2} \times B = \begin{pmatrix} 56.9 \\ 42.2 \end{pmatrix} \dfrac{\text{kN}}{\text{m}}$ ❹

effective $V'_d = V_d - U_d = \begin{pmatrix} 346.7 \\ 264 \end{pmatrix} \dfrac{\text{kN}}{\text{m}}$

Design vertical actions (favourable)

total $V_{d,fav} = \gamma_{G,fav} \times W_{Gk} = \begin{pmatrix} 256.7 \\ 256.7 \end{pmatrix} \dfrac{\text{kN}}{\text{m}}$

water upthrust $U_{d,fav} = \gamma_{G,fav} \times \dfrac{u_h}{2} \times B = \begin{pmatrix} 42.2 \\ 42.2 \end{pmatrix} \dfrac{\text{kN}}{\text{m}}$

effective $V'_{d,fav} = V_{d,fav} - U_{d,fav} = \begin{pmatrix} 214.6 \\ 214.6 \end{pmatrix} \dfrac{\text{kN}}{\text{m}}$

Active earth pressure coefficient $K_a = \dfrac{1 - \sin(\varphi_d)}{1 + \sin(\varphi_d)} = \begin{pmatrix} 0.26 \\ 0.331 \end{pmatrix}$

Design thrust on virtual back and destabilizing moments (about toe)

Dry backfill $P_{ad_1} = \overrightarrow{\left(\dfrac{\gamma_G \times K_a \times \sigma'_{vk,w} \times d_w}{2}\right)} = \begin{pmatrix} 7.1 \\ 6.7 \end{pmatrix} \dfrac{\text{kN}}{\text{m}}$

Moment from dry backfill $M_{d_1} = P_{ad_1} \times \left(h_w + \frac{d_w}{3}\right) = \begin{pmatrix} 17.7 \\ 16.8 \end{pmatrix} \frac{kNm}{m}$

Wet backfill (part) $P_{ad_2} = \overrightarrow{\left(\frac{\gamma_G \times K_a \times \sigma'_{vk,w} \times h_w}{2}\right)} = \begin{pmatrix} 9.5 \\ 8.9 \end{pmatrix} \frac{kN}{m}$

Moment from wet backfill (part) $M_{d_2} = P_{ad_2} \times \left(\frac{2\ h_w}{3}\right) = \begin{pmatrix} 12.6 \\ 11.9 \end{pmatrix} \frac{kNm}{m}$

Wet backfill (part) $P_{ad_3} = \overrightarrow{\left(\frac{\gamma_G \times K_a \times \sigma'_{vk,h} \times h_w}{2}\right)} = \begin{pmatrix} 15.2 \\ 14.4 \end{pmatrix} \frac{kN}{m}$

Moment from wet backfill (part) $M_{d_3} = P_{ad_3} \times \left(\frac{h_w}{3}\right) = \begin{pmatrix} 10.1 \\ 9.6 \end{pmatrix} \frac{kNm}{m}$

Surcharge $P_{ad_4} = \overrightarrow{\left[\gamma_Q \times K_a \times q_{Qk} \times (H + d)\right]} = \begin{pmatrix} 13.6 \\ 15.1 \end{pmatrix} \frac{kN}{m}$

Moment from surcharge $M_{d_4} = P_{ad_4} \times \left(\frac{H + d}{2}\right) = \begin{pmatrix} 23.9 \\ 26.4 \end{pmatrix} \frac{kNm}{m}$

Water $U_{ad} = \overrightarrow{\left(\frac{\gamma_G \times u_h \times h_w}{2}\right)} = \begin{pmatrix} 26.5 \\ 19.6 \end{pmatrix} \frac{kN}{m}$

Moment from water $M_{d_5} = U_{ad} \times \left(\frac{h_w}{3}\right) = \begin{pmatrix} 17.7 \\ 13.1 \end{pmatrix} \frac{kNm}{m}$

Moment from water uplift $M_{d_6} = U_d \times \left(\frac{2\ B}{3}\right) = \begin{pmatrix} 163.2 \\ 120.9 \end{pmatrix} \frac{kNm}{m}$

Total design horizontal thrust $H_{Ed} = \left(\sum_{i=1}^{4} \overrightarrow{P_{ad_i}}\right) + U_{ad} = \begin{pmatrix} 71.9 \\ 64.7 \end{pmatrix} \frac{kN}{m}$

Total design destabilizing moment $M_{Ed,dst} = \left(\sum_{i=1}^{6} \overrightarrow{M_{d_i}}\right) = \begin{pmatrix} 245.2 \\ 198.6 \end{pmatrix} \frac{kNm}{m}$

Sliding resistance

Partial factors from Sets $\begin{pmatrix} R1 \\ R1 \end{pmatrix}$: $\gamma_{Rh} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$ and $\gamma_{Rv} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$

Design drained sliding resistance (ignoring adhesion, as required by EN 1997-1 exp. 6.3a) $H_{Rd} = \overrightarrow{\left[\frac{(V_{d,fav} - U_d) \times \tan(\delta_{d,fdn})}{\gamma_{Rh}}\right]} = \begin{pmatrix} 72.7 \\ 78.1 \end{pmatrix} \frac{kN}{m}$ ❺

Eccentricity of loads

Design stabilizing moment

$$M_{Ed,stb} = \gamma_G \times M_{Ek,stb} + \gamma_Q \times Q_{Qk} \times \frac{(B + x)}{2} = \begin{pmatrix} 944.3 \\ 716.7 \end{pmatrix} \frac{kNm}{m}$$

Eccentricity of load $e_B = \overrightarrow{\left|\left(\frac{B}{2} - \frac{M_{Ed,stb} - M_{Ed,dst}}{V_d - U_d}\right)\right|} = \begin{pmatrix} 0.13 \\ 0.19 \end{pmatrix} m$

Load is within middle-third of base if $e_B \le \frac{B}{6} = 0.72\, m$

Effective breadth is $B' = B - 2\, e_B = \begin{pmatrix} 4.03 \\ 3.93 \end{pmatrix} m$ and area $A' = B'$

Drained bearing capacity factors

$$N_q = \overrightarrow{\left[e^{(\pi \tan(\varphi_{d,fdn}))} \left(\tan\left(45° + \frac{\varphi_{d,fdn}}{2}\right)\right)^2\right]} = \begin{pmatrix} 11.9 \\ 7.3 \end{pmatrix}$$

$$N_c = \overrightarrow{\left[(N_q - 1) \times \cot(\varphi_{d,fdn})\right]} = \begin{pmatrix} 22.3 \\ 16.1 \end{pmatrix}$$

$$N_\gamma = \overrightarrow{\left[2\, (N_q - 1) \times \tan(\varphi_{d,fdn})\right]} = \begin{pmatrix} 10.6 \\ 4.9 \end{pmatrix}$$

Drained inclination factors

Effective length $L' = \infty\ m$, hence exponent $m_B = \frac{\left(2 + \frac{B'}{L'}\right)}{\left(1 + \frac{B'}{L'}\right)} = \begin{pmatrix} 2 \\ 2 \end{pmatrix}$

$$i_q = \overrightarrow{\left[1 - \left(\frac{H_{Ed}}{V'_d + A' \times c'_{d,fdn} \times \cot(\varphi_{d,fdn})}\right)\right]^{m_B}} = \begin{pmatrix} 0.66 \\ 0.62 \end{pmatrix}$$

$$i_c = \overrightarrow{\left[i_q - \left[\frac{(1 - i_q)}{N_c \times \tan(\varphi_{d,fdn})} \right] \right]} = \begin{pmatrix} 0.63 \\ 0.56 \end{pmatrix}$$

$$i_\gamma = \overrightarrow{\left[1 - \left(\frac{H_{Ed}}{V'_d + A' \times c'_{d,fdn} \times \cot(\varphi_{d,fdn})} \right) \right]^{m_B+1}} = \begin{pmatrix} 0.54 \\ 0.49 \end{pmatrix}$$

Drained bearing resistance

Drained overburden at foundation base $\sigma'_{vk,b} = \gamma_{k,fdn} \times (d - \Delta H) = 4.4\ kPa$

Ultimate resistance...

from overburden $q_{ult_1} = \overrightarrow{(N_q \times i_q \times \sigma'_{vk,b})} = \begin{pmatrix} 34.6 \\ 19.9 \end{pmatrix}$ kPa

from cohesion $q_{ult_2} = \overrightarrow{(N_c \times i_c \times c'_{d,fdn})} = \begin{pmatrix} 70.4 \\ 36.1 \end{pmatrix}$ kPa

from self-weight $q_{ult_3} = \overrightarrow{\left[N_\gamma \times i_\gamma \times (\gamma_{k,fdn} - \gamma_w) \times \frac{B'}{2} \right]} = \begin{pmatrix} 140.8 \\ 57.4 \end{pmatrix}$ kPa

total $q_{ult} = \sum_{i=1}^{3} q_{ult_i} = \begin{pmatrix} 245.9 \\ 113.5 \end{pmatrix}$ kPa

Design resistance $q'_{Rd} = \frac{q_{ult}}{\gamma_{Rv}} = \begin{pmatrix} 245.9 \\ 113.5 \end{pmatrix}$ kPa

Verifications

For drained sliding $H_{Ed} = \begin{pmatrix} 71.9 \\ 64.7 \end{pmatrix} \frac{kN}{m}$ and $H_{Rd} = \begin{pmatrix} 72.7 \\ 78.1 \end{pmatrix} \frac{kN}{m}$

Degree of utilization $\Lambda_{GEO,1} = \frac{H_{Ed}}{H_{Rd}} = \begin{pmatrix} 99 \\ 83 \end{pmatrix}$ % ❻

For drained bearing $q'_{Ed} = \frac{V'_d}{B'} = \begin{pmatrix} 85.9 \\ 67.2 \end{pmatrix}$ kPa and $q'_{Rd} = \begin{pmatrix} 245.9 \\ 113.5 \end{pmatrix}$ kPa

Degree of utilization $\Lambda_{GEO,1} = \frac{q'_{Ed}}{q'_{Rd}} = \begin{pmatrix} 35 \\ 59 \end{pmatrix}$ %

Design is unacceptable if degree of utilization is > 100%