## Example 7.4
## Basement subject to uplift
## Verification of stability against uplift (UPL)

One-storey basement

*Design situation*

Consider a three-storey building which applies a self-weight loading at foundation level estimated to be $w_{Gk} = 30kPa$ (permanent) and carries imposed loads on its floors and roof amounting to $q_{Qk} = 15kPa$ (variable). The building is to be supported by a one-storey basement of width $B = 18m$ and depth $D = 4.5m$. The basement walls are $t_w = 400mm$ thick, its floors $t_f = 250mm$ thick, and its base slab $t_b = 500mm$ thick. The characteristic weight density of reinforced concrete is $\gamma_{ck} = 25\frac{kN}{m^3}$, as per EN 1991-1-1.

The ground profile comprises 20m of dense sand and groundwater levels are close to ground level. The sand's characteristic weight density is $\gamma_k = 19\frac{kN}{m^3}$, its angle of shearing resistance $\varphi_k = 38°$, and its 'superior' angle of shearing resistance $\varphi_{k,sup} = 45°$.The weight density of water should be taken as $\gamma_w \equiv 9.81\frac{kN}{m^3}$.

*Actions*

The characteristic water pressure acting on the underside of the basement is $u_k = \gamma_w \times D = 44.1\,kPa$, giving a resultant destabilizing action underneath the basement of $U_{Gk} = u_k \times B = 795\frac{kN}{m}$. Characteristic actions from the super-structure are $W_{Gk,sup} = w_{Gk} \times B = 540\frac{kN}{m}$ (permanent) and $Q_{Qk,sup} = q_{Qk} \times B = 270\frac{kN}{m}$ (variable). ❶

Characteristic self-weight of the sub-structure (basement) is:

from the walls $W_{Gk,w} = 2 \times t_w \times D \times \gamma_{ck} = 90 \frac{kN}{m}$

from the floors $W_{Gk,f} = t_f \times \left(B - 2t_f\right) \times \gamma_{ck} = 109.4 \frac{kN}{m}$

from the base slab $W_{Gk,b} = t_b \times \left(B - 2t_f\right) \times \gamma_{ck} = 218.8 \frac{kN}{m}$

total weight $W_{Gk,sub} = W_{Gk,w} + W_{Gk,f} + W_{Gk,b} = 418 \frac{kN}{m}$ ❶

Total self-weight of the building is $W_{Gk} = W_{Gk,sup} + W_{Gk,sub} = 958 \frac{kN}{m}$.

*Effects of actions*

Partial factors on destabilizing permanent and variable actions are $\gamma_{G,dst} = 1.1$ and $\gamma_{Q,dst} = 1.5$ and on stabilizing permanent actions $\gamma_{G,stb} = 0.9$ . Thus the destabilizing vertical action is

$V_{d,dst} = \gamma_{G,dst} \times U_{Gk} = 874.1 \frac{kN}{m}$ and the stabilizing vertical action

$V_{d,stb} = \gamma_{G,stb} \times W_{Gk} = 862.3 \frac{kN}{m}$. ❷

*Material properties*

The sand's characteristic angle of shearing resistance is $\varphi_k = 38°$, giving an

active earth pressure coefficient $K_{a,k} = \frac{1 - \sin\left(\varphi_k\right)}{1 + \sin\left(\varphi_k\right)} = 0.238$ and angle of

wall friction $\delta_k = \frac{2}{3}\varphi_k = 25.3°$. Thus $\beta_k = K_{a,k} \tan\left(\delta_k\right) = 0.113$ ❸.

The partial factor on the coefficient of shearing resistance $\gamma_\varphi = 1.25$ gives

a design angle of shearing resistance $\varphi_d = \tan^{-1}\left(\frac{\tan\left(\varphi_k\right)}{\gamma_\varphi}\right) = 32°$. Thus the

active earth pressure coefficient increases to $K_{a,d} = \frac{1 - \sin\left(\varphi_d\right)}{1 + \sin\left(\varphi_d\right)} = 0.307$

while the angle of wall friction reduces to $\delta_d = \frac{2}{3}\varphi_d = 21.3°$. Thus

$\beta_{d,inf} = K_{a,d}\tan(\delta_d) = 0.12$ . ❹

We need to check that a lower β is not obtained with the superior angle of shearing resistance $\varphi_{k,sup} = 45°$ and partial factor $\gamma_{\varphi,sup} = \frac{1}{\gamma_\varphi} = 0.8$ . The superior design angle of shearing resistance is then

$$\varphi_{d,sup} = \tan^{-1}\left(\frac{\tan(\varphi_{k,sup})}{\gamma_{\varphi,sup}}\right) = 51.3°, \text{ giving}$$

$$K_{a,d,sup} = \frac{1-\sin(\varphi_{d,sup})}{1+\sin(\varphi_{d,sup})} = 0.123 \quad \text{and} \quad \delta_{d,sup} = \frac{2}{3}\varphi_{d,sup} = 34.2°.$$

Hence $\beta_{d,sup} = K_{a,d,sup} \times (\tan(\delta_{d,sup})) = 0.084$ ❺

Thus $\beta_d = \min(\beta_{d,inf}, \beta_{d,sup}) = 0.084$

*Resistance*

The average vertical effective stress down the basement wall is:

$$\sigma'_v = \frac{(\gamma_k - \gamma_w) \times D}{2} = 20.7\,kPa$$

The characteristic resistance along the basement walls is given by:

$$R_k = \beta_k \times \frac{(\gamma_k - \gamma_w) \times D^2}{2} = 10.5\frac{kN}{m}$$

The design resistance along the basement walls is given by:

$$R_d = \beta_d \times \frac{(\gamma_k - \gamma_w) \times D^2}{2} = 7.8\frac{kN}{m}$$

*Verification of stability against uplift*

The degree of utilization is $\boxed{\Lambda_{UPL} = \frac{V_{d,dst}}{V_{d,stb} + R_d} = 100\%}$ ❻

The design is unacceptable if the degree of utilization is > 100%

The traditional lumped factor of safety for this design situation is:

$$F = \frac{W_{Gk,sup} + W_{Gk,sub} + R_k}{U_{Gk}} = 1.22$$ ❻

## Two-storey basement

*Design situation*

The building considered above is now required to have a two-storey basement with depth $D = 7.5m$.

*Actions*

The characteristic water pressure acting on the underside of the basement is $u_k = \gamma_w \times D = 73.6\,kPa$, giving a resultant destabilizing action underneath the basement of $U_{Gk} = u_k \times B = 1324 \frac{kN}{m}$. Characteristic actions from the super-structure remain $W_{Gk,sup} = 540 \frac{kN}{m}$ (permanent) and $Q_{Qk,sup} = 270 \frac{kN}{m}$ (variable). The characteristic self-weight of the two floors is now $W_{Gk,f} = 2t_f \times \left(B - 2t_f\right) \times \gamma_{ck} = 218.8 \frac{kN}{m}$ and of the walls $W_{Gk,w} = 2 \times t_w \times D \times \gamma_{ck} = 150 \frac{kN}{m}$, resulting in a total weight of sub-structure $W_{Gk,sub} = W_{Gk,w} + W_{Gk,f} + W_{Gk,b} = 588 \frac{kN}{m}$. Hence the total self-weight of the building is now $W_{Gk} = W_{Gk,sup} + W_{Gk,sub} = 1128 \frac{kN}{m}$.

*Effects of actions*

The destabilizing vertical action is $V_{d,dst} = \gamma_{G,dst} \times U_{Gk} = 1456.8 \frac{kN}{m}$ and the stabilizing vertical action $V_{d,stb} = \gamma_{G,stb} \times W_{Gk} = 1014.8 \frac{kN}{m}$.

*Material properties*

Are unchanged.

*Resistance*

The average vertical effective stress down the basement wall is:

$$\sigma'_v = \frac{\left(\gamma_k - \gamma_w\right) \times D}{2} = 34.5\,kPa$$

The characteristic resistance along the basement walls is given by:

$$R_k = \beta_k \times \frac{(\gamma_k - \gamma_w) \times D^2}{2} = 29.1 \frac{kN}{m}$$

The design resistance along the basement walls is given by:

$$R_d = \beta_d \times \frac{(\gamma_k - \gamma_w) \times D^2}{2} = 21.6 \frac{kN}{m}$$

*Verification of stability against uplift*

The degree of utilization is $\Lambda_{UPL} = \frac{V_{d,dst}}{V_{d,stb} + R_d} = 141\%$ ❼

The design is unacceptable if the degree of utilization is > 100%

The traditional lumped factor of safety for this design situation is:

$$F = \frac{W_{Gk,sup} + W_{Gk,sub} + R_k}{U_{Gk}} = 0.87$$ ❼

*Additional resistance from tension piles*

To overcome the shortfall in stabilizing actions and resistance, the basement will be held down by $n = 4$ rows of tension piles, each pile $L = 10m$ long and $d = 450mm$ in diameter. The piles will be installed using a contiguous flight auger. Pile rows will be spaced at $s = 5m$ spacing along the building (i.e. into the plane of the drawing). An earth pressure coefficient $K_s = 1$ is assumed in order to determine skin friction along the pile shaft. ❽

The average vertical effective stress along the pile shafts is:

$$\sigma'_{v,pile} = (\gamma_k - \gamma_w)\left(D + \frac{L}{2}\right) = 114.9 \text{ kPa.}$$

The characteristic resistance of each pile is given by:

$$R_{k,pile} = \pi d \times L \times \sigma'_{v,pile} \times \tan(\delta_k) \times K_s = 768.8 \text{ kN}$$

and the design resistance by:

$$R_{d,pile} = \pi d \times L \times \sigma'_{v,pile} \times \frac{\tan(\delta_k)}{\gamma_\varphi} \times K_s = 615.1 \text{ kN}$$

Hence the total characteristic resistance is now:

$$R_k = R_k + \left(\frac{n}{s}\right) \times R_{k,pile} = 644.2 \frac{kN}{m}$$

and the total design resistance is:

$$R_d = R_d + \left(\frac{n}{s}\right) \times R_{d,pile} = 513.7 \frac{kN}{m}$$ ❾

*Verification of stability against uplift (with tension piles)*

The degree of utilization is $\Lambda_{UPL} = \frac{V_{d,dst}}{V_{d,stb} + R_d} = 95\,\%$ ❿

The design is unacceptable if the degree of utilization is > 100%

The traditional lumped factor of safety for this design situation is:

$$F = \frac{W_{Gk,sup} + W_{Gk,sub} + R_k}{U_{Gk}} = 1.34$$ ❿