European Commission

Worked examples – HYD and UPL limit states

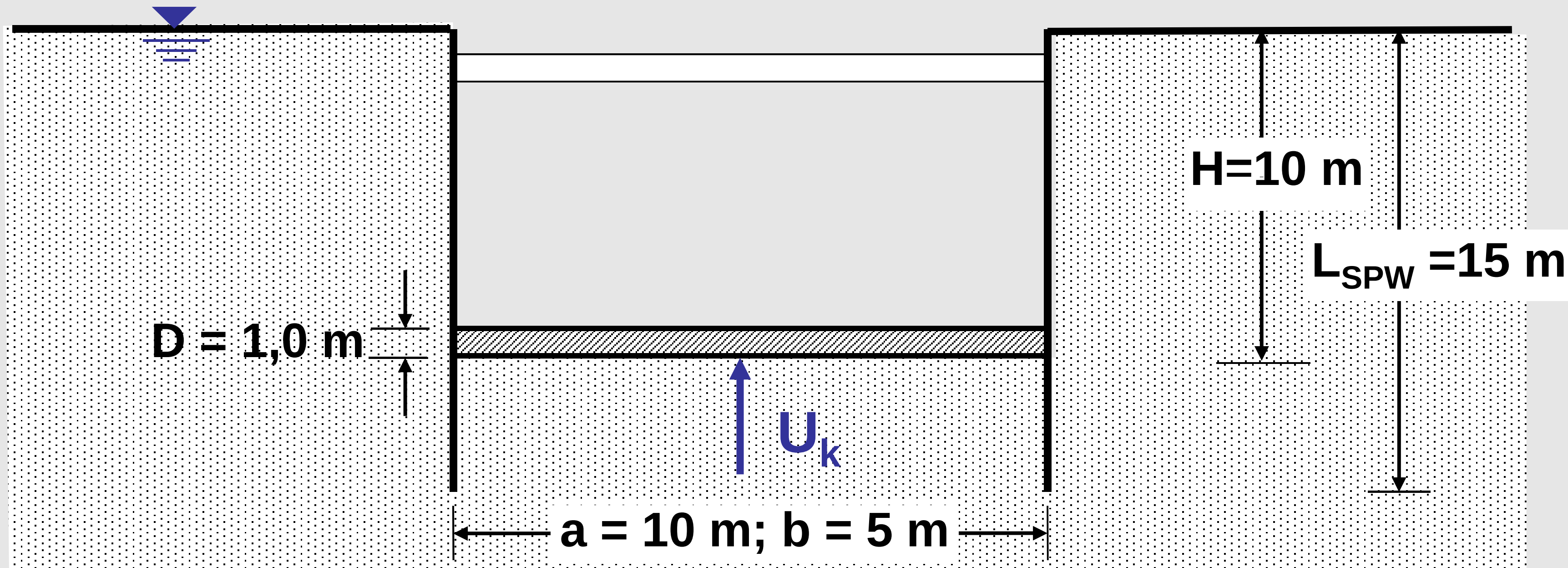
Dr. Bernd Schuppener

German Federal Waterways Engineering and Research Institute, Karlsruhe

Past Chairman of CEN TC250/SC 7

Worked example: Verification of uplift of a base slab in an excavation

Example: verification of failure by uplift UPL



$\varphi'_k = 32{,}5°$ $\quad$ $\gamma_{conrete} = 24{,}0\ kN/m^3$

$\gamma' = 10\ kN/m^3$ $\quad$ $\gamma_{Steel} \cdot d = 2{,}34\ kN/m^2$

Waterpressure: $U_k = H \cdot \gamma_w \cdot b \cdot a = 5000\ kN$

EN 1997-1: 2.4.7.4 Verification of uplift

(1)P Verification for uplift (UPL) shall be carried out by checking that the design value of the combination of **destabilising** permanent and variable vertical actions ($V_{dst;d}$) is less than or equal to the sum of the design value of the **stabilising** permanent vertical actions ($G_{stb;d}$) and of the design value of any additional resistance to uplift (R_d):

$$\boldsymbol{V_{dst,d} \leq G_{stb;d} + R_d} \qquad (2.8)$$

where

$$\boldsymbol{V_{dst,d} = G_{dst;d} + Q_{dst;d}}$$

(2) Additional resistance to uplift may also be treated as a stabilising permanent vertical action ($G_{stb;d}$).

UPL partial factors and model factor

Factor type	Factor	EN 1997-1	German NA and DIN 1054	Irish NA
Permanent unfavourable action	$\gamma_{G;dst}$	1.0	1.0	1.0
Permanent favourable action	$\gamma_{G;stb}$	0.9	0.9	0.9
Variable unfavourable action	$\gamma_{Q;dst}$	1.5	1.5	1.5
Angle of shearing resistance	γ_{ϕ}	1.25	1.25	1.25
Pile tensile resistance	$\gamma_{s;t}$	1.4	1.4	2.0
Model factor on wall resistance	η	-	0.8	-

UPL- verification with the weight of the structure only

For the verifications the following quantities are needed:

Self-weight base-slab:

Base-slab: $d = 1{,}0$ m, $\gamma_{concrete} = 24{,}0$ kN/m³:

Base-area $A = a \cdot b = 10{,}0 \cdot 5{,}0 = 50{,}00$ m²

$G_{concrete} = A \cdot d \cdot \gamma_{concrete}$

$G_{concrete} = 50 \cdot 1{,}0 \cdot 24{,}0 =$ **1200 kN**.

Self weight sheet-pile-wall: $d_{SPW} = 0{,}03$ m, $\gamma_{Steel} = 78{,}0$ kN/m³

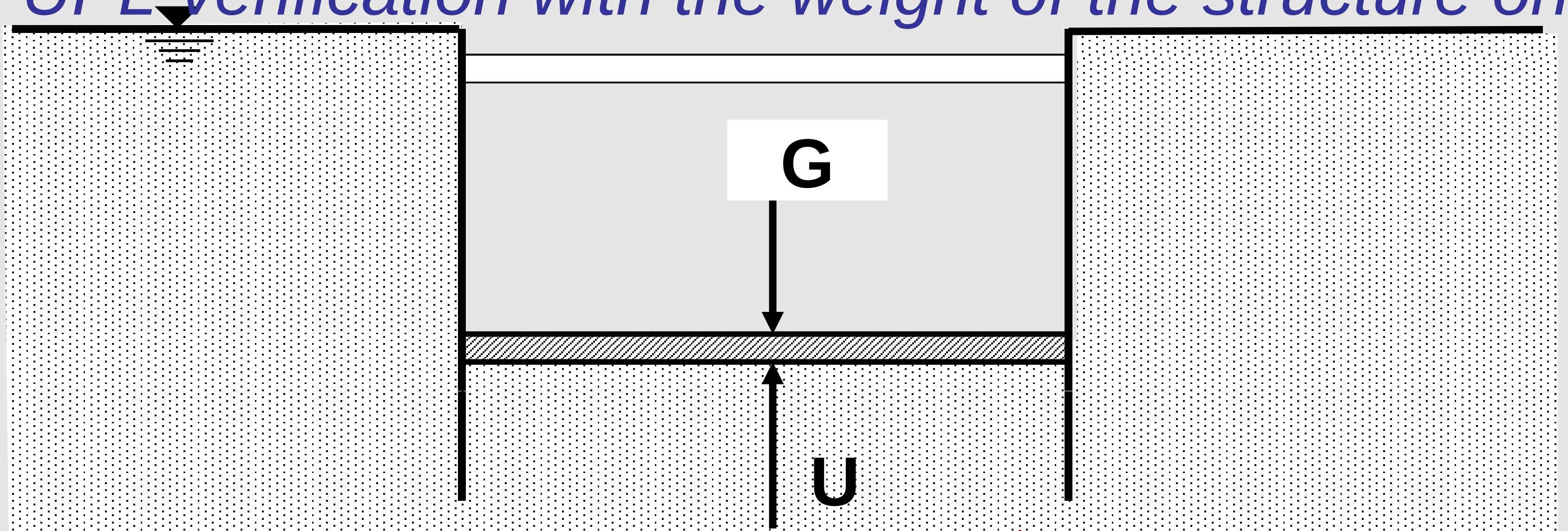
Weight per unit area: $g = 78{,}0 \cdot 0{,}03 = 2{,}34$ kN/m²,

$G_{SPW} = L_{SPW} \cdot 2 \cdot (a + b) \cdot g = 15 \cdot 30 \cdot 2{,}34 =$ **1053 kN**

Total characteristic weight of the structure:

$\mathbf{G_k} = G_{concrete} + G_{SPW} = 1200 + 1053 =$ **2253 kN**

UPL-verification with the weight of the structure only



Required: $V_{dst,d} \leq G_{stb;d} + \cancel{R_d}$ **eq. (2.8)**

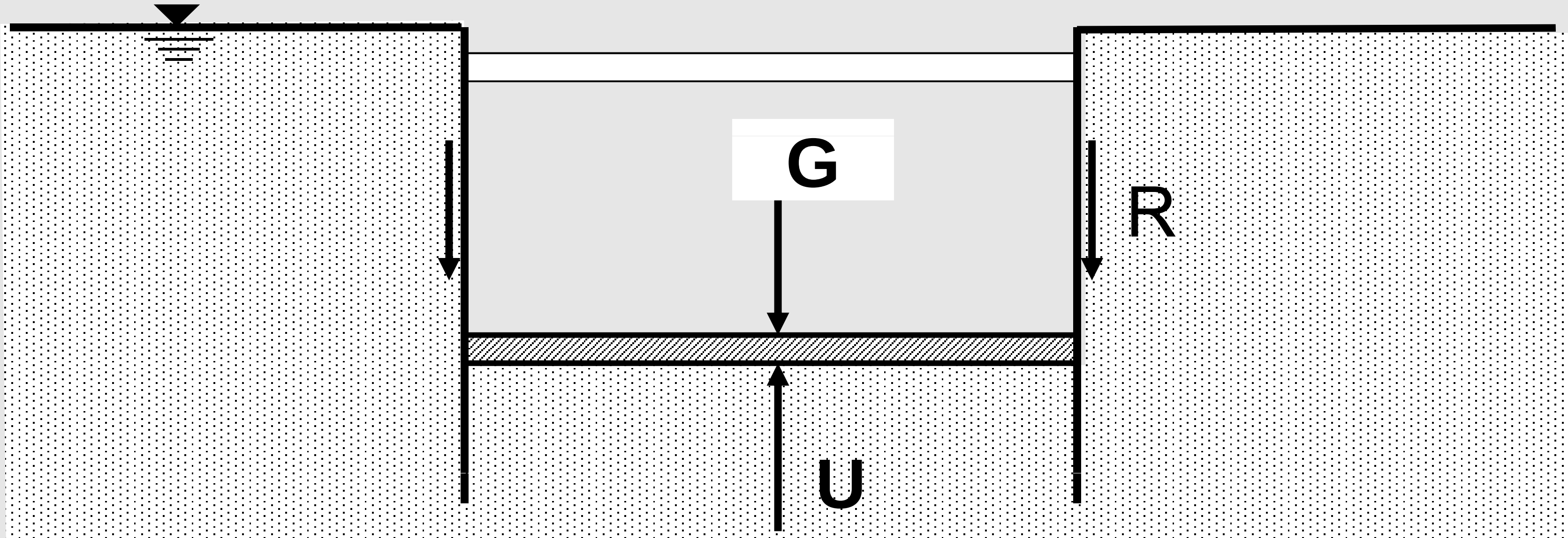
$$V_{dst,d} = U_d \leq G_d$$

$$U_k \cdot \gamma_{G,dst} \leq G_k \cdot \gamma_{G,stb}$$

But: 5000 · 1,00 = **5000** kN **>** 2253 · 0,90 = **2028** kN

Hence UPL requirement not satisfied!

UPL-verification including wall frictional resistance R



$$V_{dst,d} \leq G_{stb;d} + R_d$$

$$U_d \leq G_d + R_d$$

$$U_k \cdot \gamma_{G,dst} \leq (G_k + R_k) \cdot \gamma_{G,stb}$$

Verification of failure by uplift UPL – frictional resistance R

The characteristic value of the wall frictional resistance R_k will be treated as a stabilising action determined as the vertical component of the characteristic active earth pressure reduced by a model factor of η = 0,80:

$$R_k = E_{ah,k} \cdot \tan \delta_a \cdot \eta$$

The wall friction angle is assumed to be $\delta_k = 2/3\ \varphi'_k$. For horizontal surface area and vertical wall the earth pressure coefficient is $K_{ah,k}$ = 0,25 (from Fig. C 1.1 of EN 1997-1 for φ_k'= 32.5°) and tan δ_a = 0,397. The earth pressure is assumed to act only on the outer surface of the sheet pile wall:

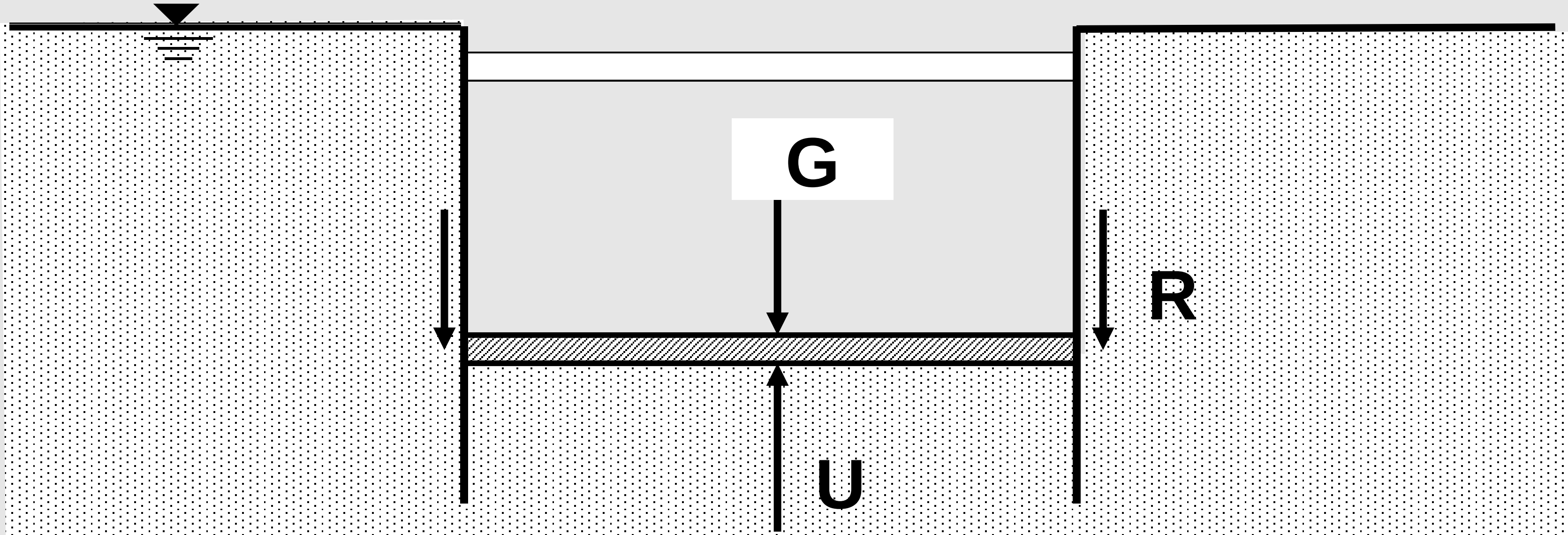
$$E_{ah,k} = 2 \cdot (a + b) \cdot 0{,}5 \cdot L_{SPW}^2 \cdot \gamma' \cdot K_{ah,k}$$

$$E_{ah,k} = 30 \cdot 0{,}5 \cdot 15^2 \cdot 10 \cdot 0{,}25 = 8437 \text{ kN}$$

$$\mathbf{R_k} = E_{ah,k} \cdot \tan \delta_k \cdot \eta$$

$$\mathbf{R_k} = 8437 \cdot 0{,}397 \cdot 0{,}8 = \mathbf{2680\ kN}$$

UPL - including wall frictional resistance



Require: $\mathbf{U_d} \leq \mathbf{G_d} + \mathbf{R_d}$

$$\mathbf{U_k} \cdot \gamma_{\mathbf{G,dst}} \leq (\mathbf{G_k} + \mathbf{R_k}) \cdot \gamma_{\mathbf{G,stb}}$$

But: 5000 · 1,00 = **5000** > (2253+2680) · 0,90 = **4400** kN

Hence UPL requirement is not satisfied

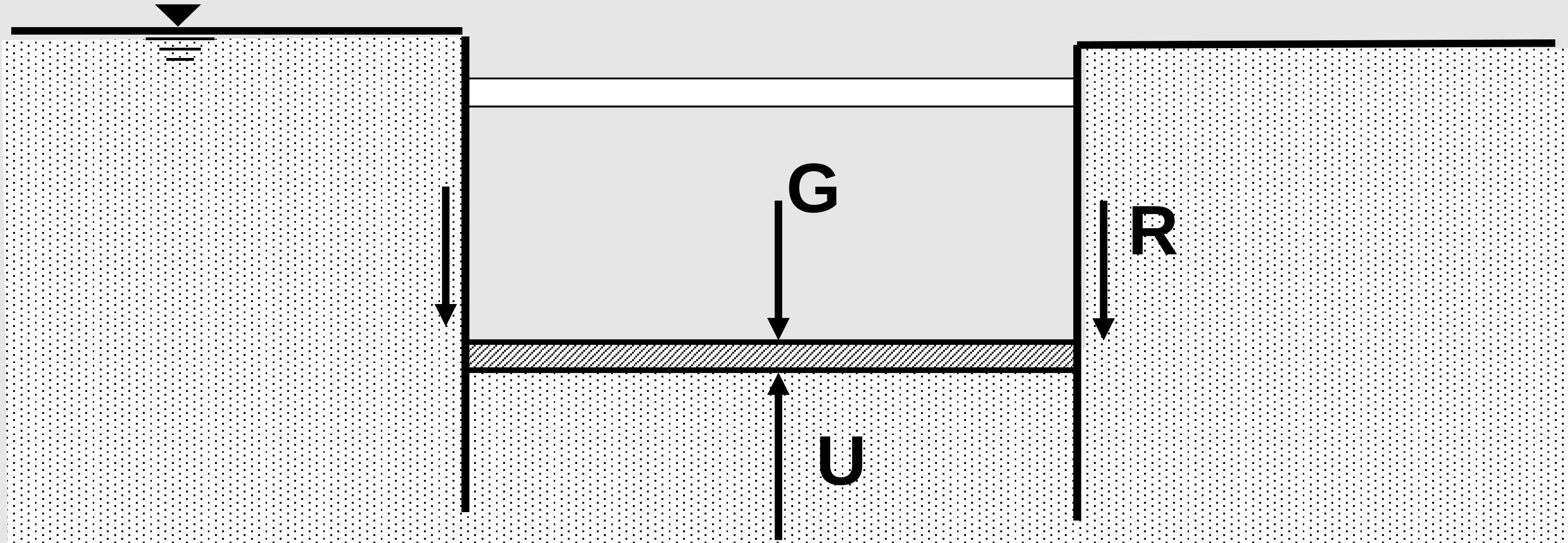
Example: Irish verification of uplift failure for UPL

<u>Calculation of R_d</u>

Using $\varphi'_{k,inf}$ = 32,5°, i.e. the inferior characteristic φ' value, and applying UPL γ_φ = 1,25 to the tan($\varphi'_{k,inf}$) to obtain to φ'_d and δ_d, gives a design wall frictional resistance R_d value that is slightly greater than the characteristic value R_k, which is not acceptable.

Hence a superior characteristic value $\varphi'_{k,sup}$ is needs to be used. This is obtained, after Bond and Harris (2008), by assuming a normal distribution for φ' and a standard deviation of 3° so that $\varphi'_{k,sup}$ = 32,5° + 2 · 1.624 · 3,0 = 42.4°. Then applying the partial factor of 1.25 as a multiplier to tan($\varphi'_{k,sup}$) gives $\varphi'_{d,sup}$ = 48.8° and hence an R_d value of **2580** kN with a margin of safety of 1.33 on the characteristic value.

Example: Irish verification of failure by uplift UPL



Require: $U_d \leq G_d + R_d$

$$U_k \cdot \gamma_{G,dst} \leq G_k \cdot \gamma_{G,stb} + R_k \, \gamma_{G,stb}$$

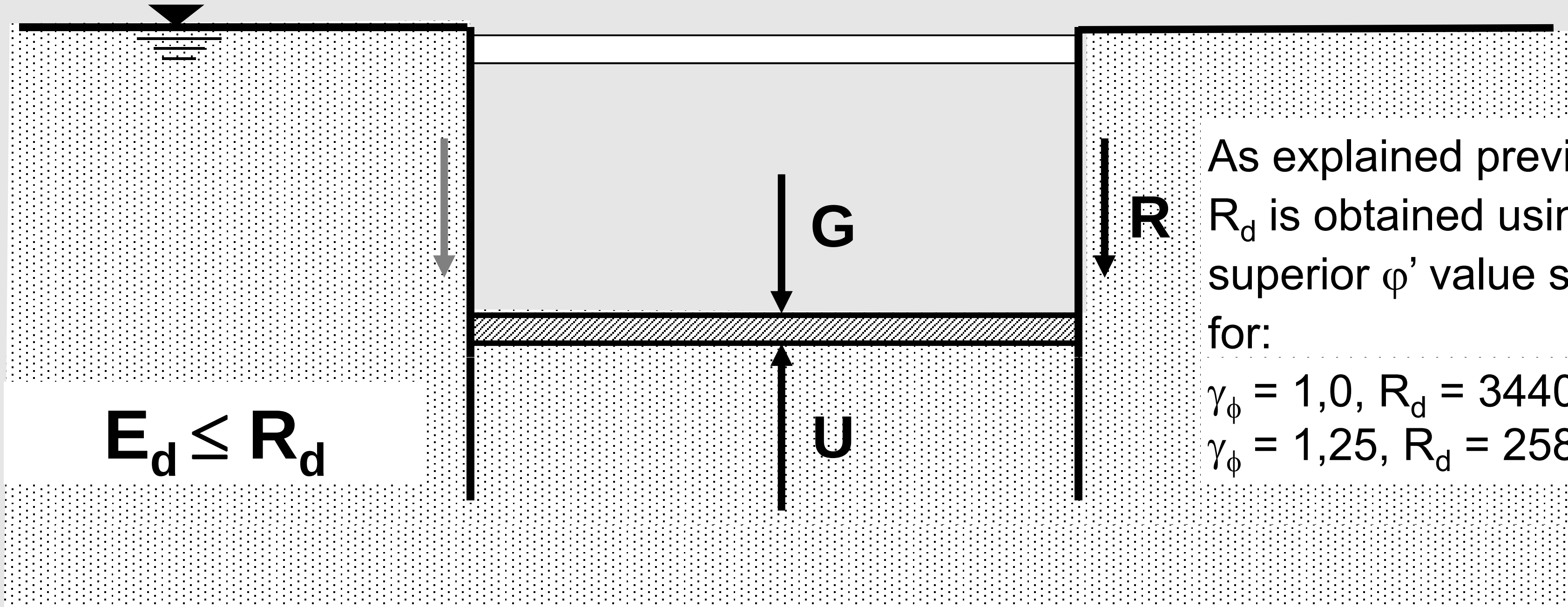
i.e. $5000 \cdot 1{,}00 = \mathbf{5000} > 2253 \cdot 0{,}90 + 2580 = \mathbf{4608}$ kN

Hence ULP requirement is not satisfied and tensile piles are required

GEO partial factors and model factor

Factor type	Factor	Irish NA DA1.C1	Irish NA DA1.C2	German NA DA2 + DIN 1054
Permanent unfavourable action, transient situation	$\gamma_{G;dst}$	1.35	1.0	**1.2**
Permanent favourable action	$\gamma_{G;stb}$	1.0	1.0	1.0
Variable unfavourable action	$\gamma_{Q;dst}$	1.5	1.3	1.5
Angle of shearing resistance	γ_{ϕ}	1.0	1.25	1.0
Pile tensile resistance	$\gamma_{s;t}$	1.25	1.6	1.4
Model factor on wall resistance	η	-	-	0.8

Irish design for GEO verification



$E_d \leq R_d$

As explained previously, R_d is obtained using the superior φ' value so that for:

$\gamma_\phi = 1{,}0$, $R_d = 3440$ kN
$\gamma_\phi = 1{,}25$, $R_d = 2580$ kN

$$E_d = U_k \cdot \gamma_G - G_k \cdot \gamma_{G,inf} = 5000 \cdot \gamma_G - 2253 \cdot \gamma_{G;inf}$$

DA1.C1: $E_d = 5000 \cdot \mathbf{1{,}35} - 2253 \cdot \mathbf{1{,}0} = \underline{4497}$ kN **>** $R_d = \underline{3440}$ kN

DA1.C2: $E_d = 5000 \cdot \mathbf{1{,}0} - 2253 \cdot \mathbf{1{,}0} = \underline{2747}$ kN < $R_d = \underline{2580}$ kN

Hence GEO ULS is not satisfied

Uplift - verification with tension piles

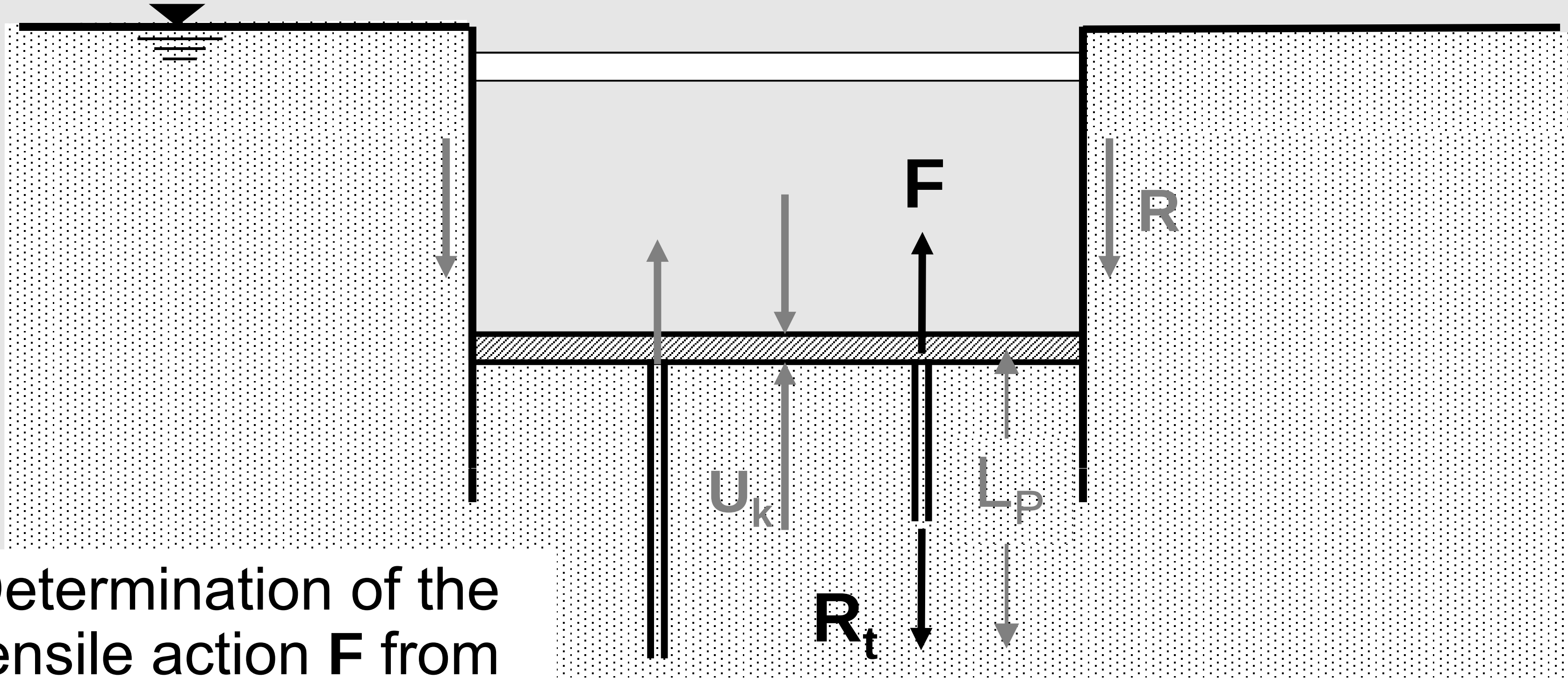
EN 1997-1

7.6.3 Piles - ground tensile resistance

(3)P For tension piles, two failure mechanisms shall be considered:

- pull-out of the piles from the ground mass;
- uplift of the structure and the block of ground containing the piles.

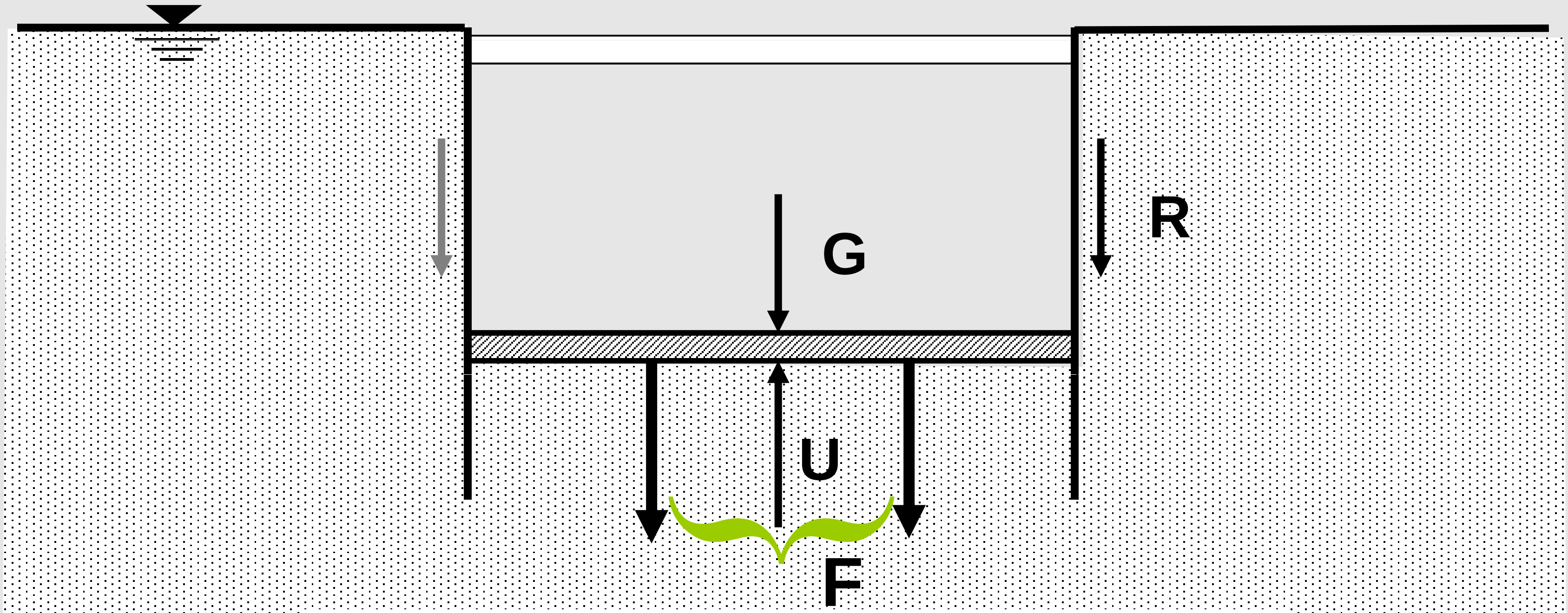
GEO - verification with tension piles



$$F_{t,d} = U_d - (R_d + G_d)$$

Determination of the tensile action **F** from the structure on the pile using ultimate limit state GEO (DA2)

Pile design (GEO) for verification of failure by uplift



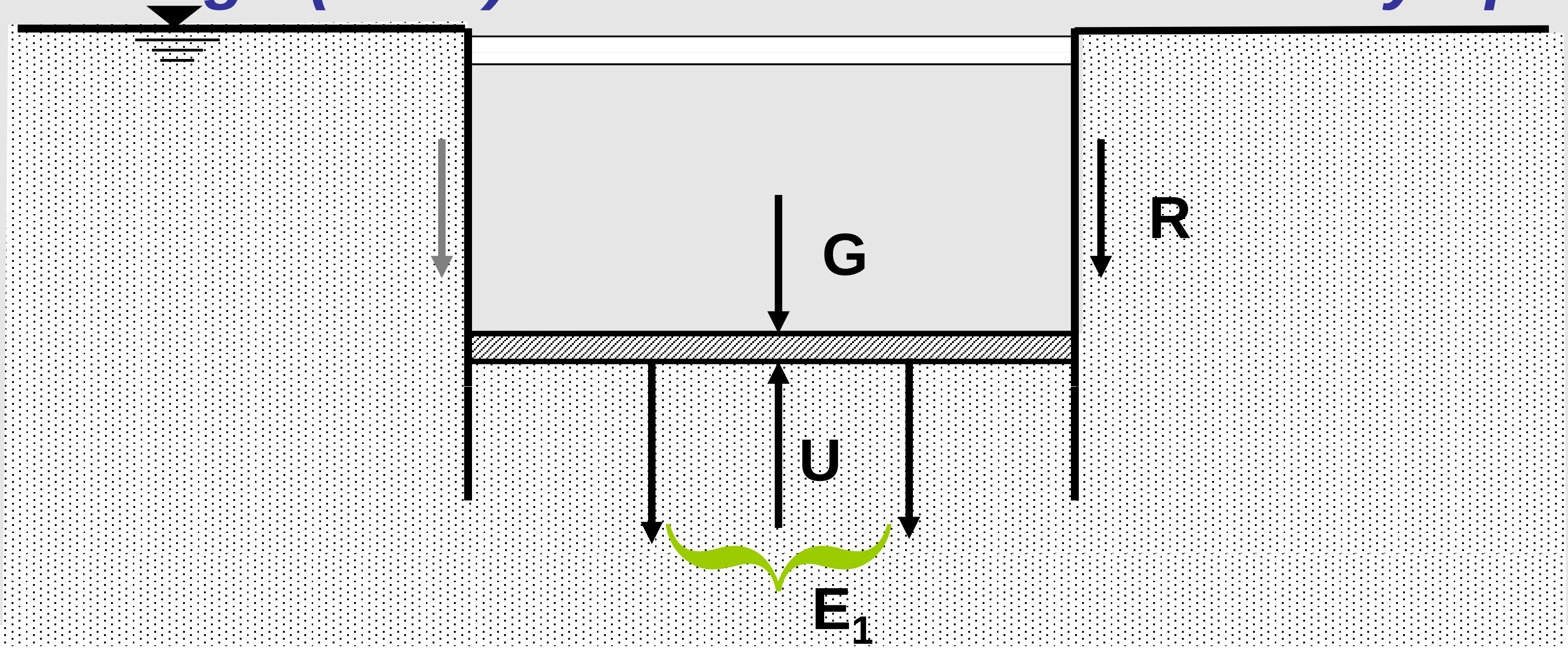
$$F_{t,d} = U_k \cdot \gamma_G - (G_k + R_k) \cdot \gamma_{G,inf}$$

$F_{t,d}$: design value of the action on the piles

γ_G = 1.20 for unfavourable actions (according to DIN 1054 for transient situations: construction period)

$\gamma_{G,inf}$ = 1.00 for favourable effects of actions

Pile design (GEO) for verification of failure by uplift



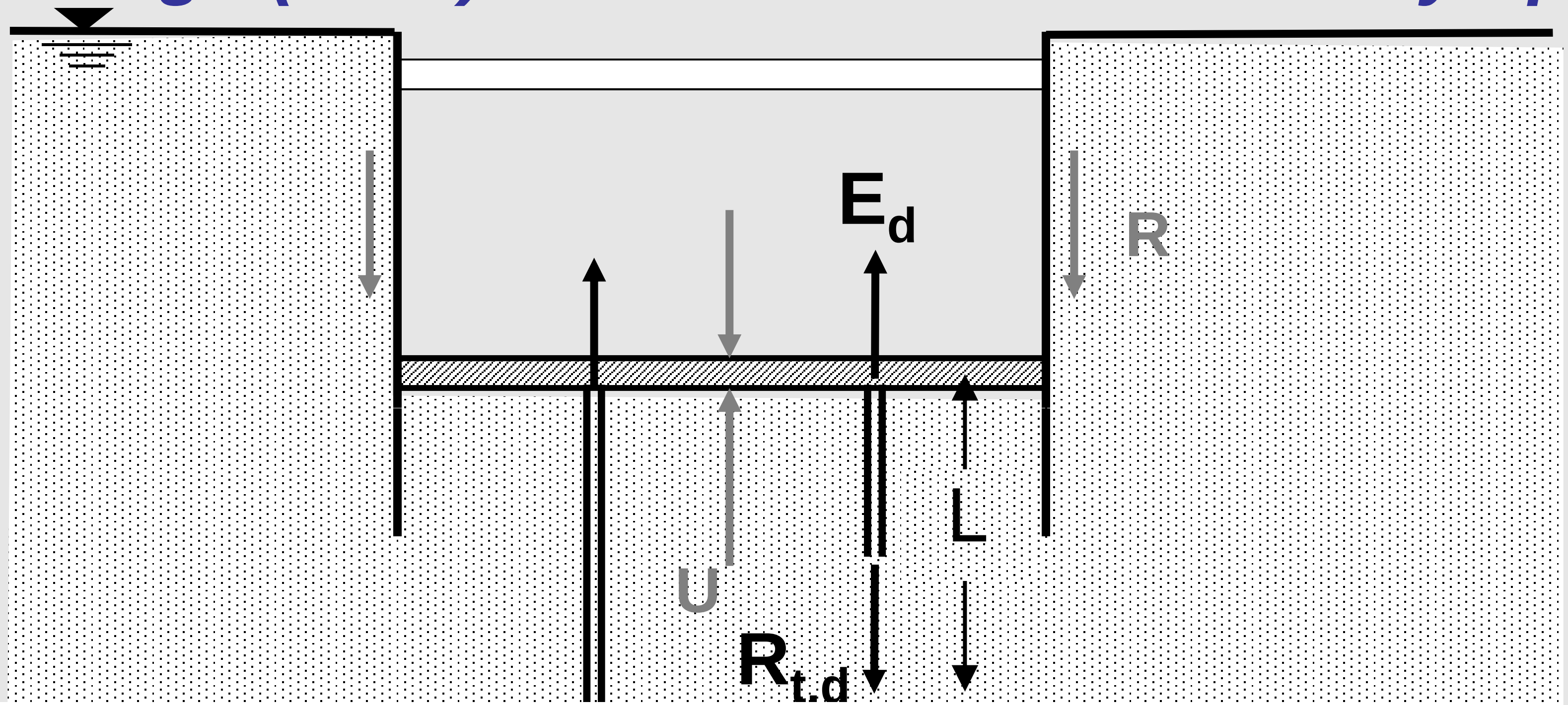
$$E_d = U_k \cdot \gamma_G - (G_k + R_k) \cdot \gamma_{G,inf}$$

$$F_{t,d} = 5000 \cdot \mathbf{1{,}20} - (2253 + 2680) \cdot \mathbf{1{,}00}$$

$$F_{t,d} = 6000 - 4933$$

$$\mathbf{F_{t,d} = 1067\ kN}$$

Pile design (GEO) for verification of failure by uplift



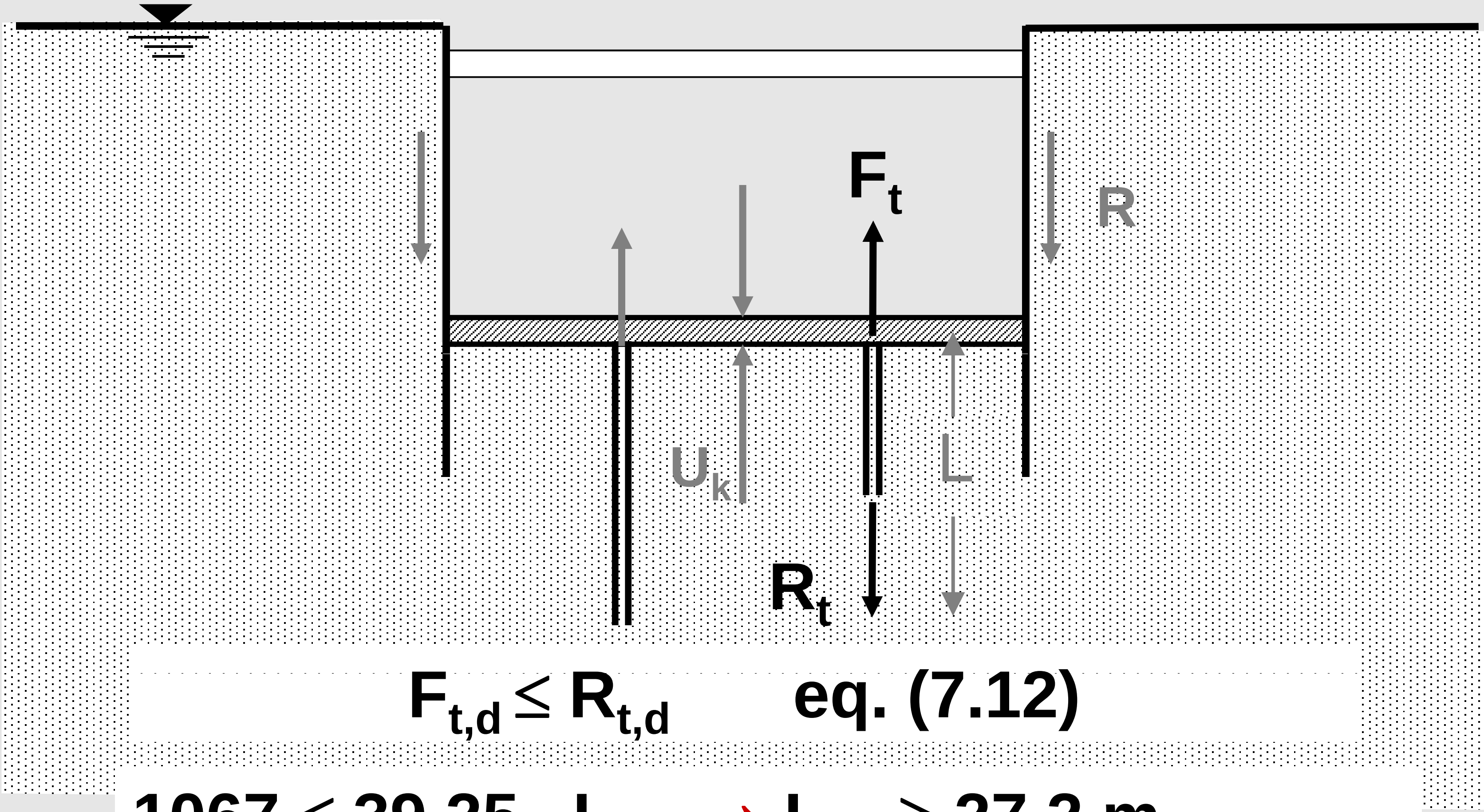
Driven piles: $L_{tot} = n \cdot L$, $D = 0{,}5$ m, $q_{s,k} = 35$ kN/m²

$\gamma_P = 1{,}40$ (DIN 1054)

$R_{t,d} = L_{tot} \cdot q_{s,k} \cdot \pi \cdot D / \gamma_P$

$$\mathbf{R_{t,d} = 39{,}25 \cdot L_{tot}}$$

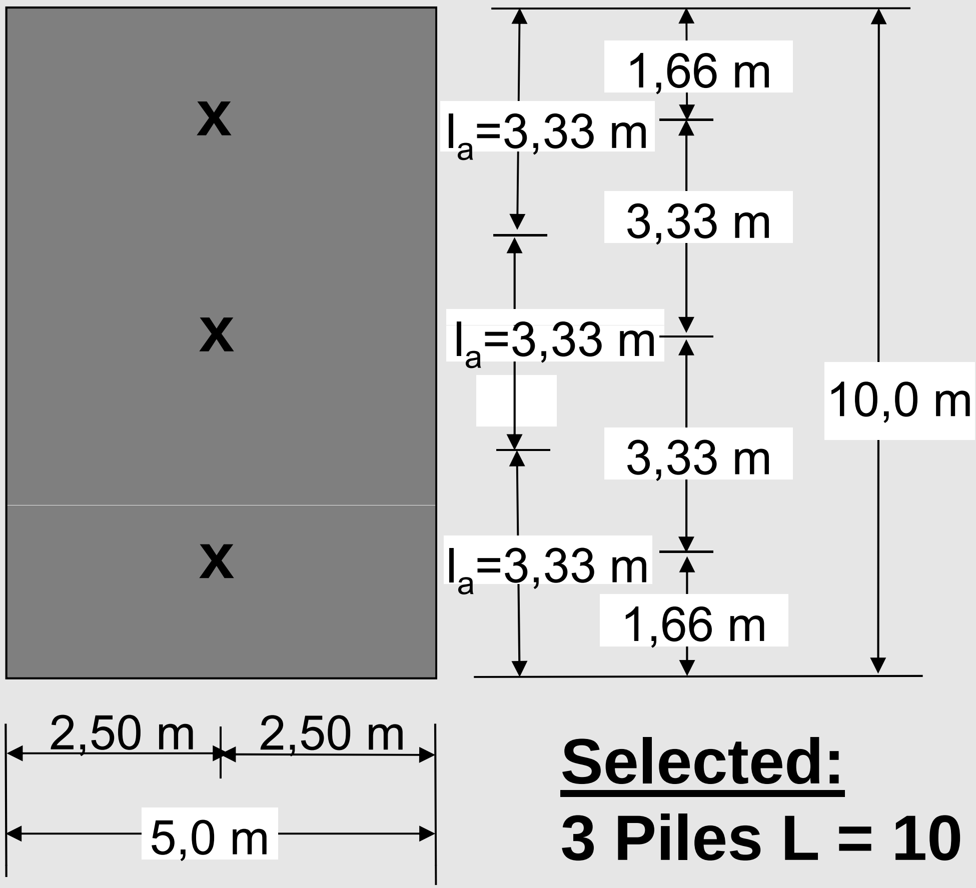
Pile design (GEO) for verification of failure by uplift



$$F_{t,d} \leq R_{t,d} \qquad \text{eq. (7.12)}$$

$$1067 \leq 39{,}25 \cdot L_{tot} \rightarrow L_{tot} \geq 27{,}2\ \text{m}$$

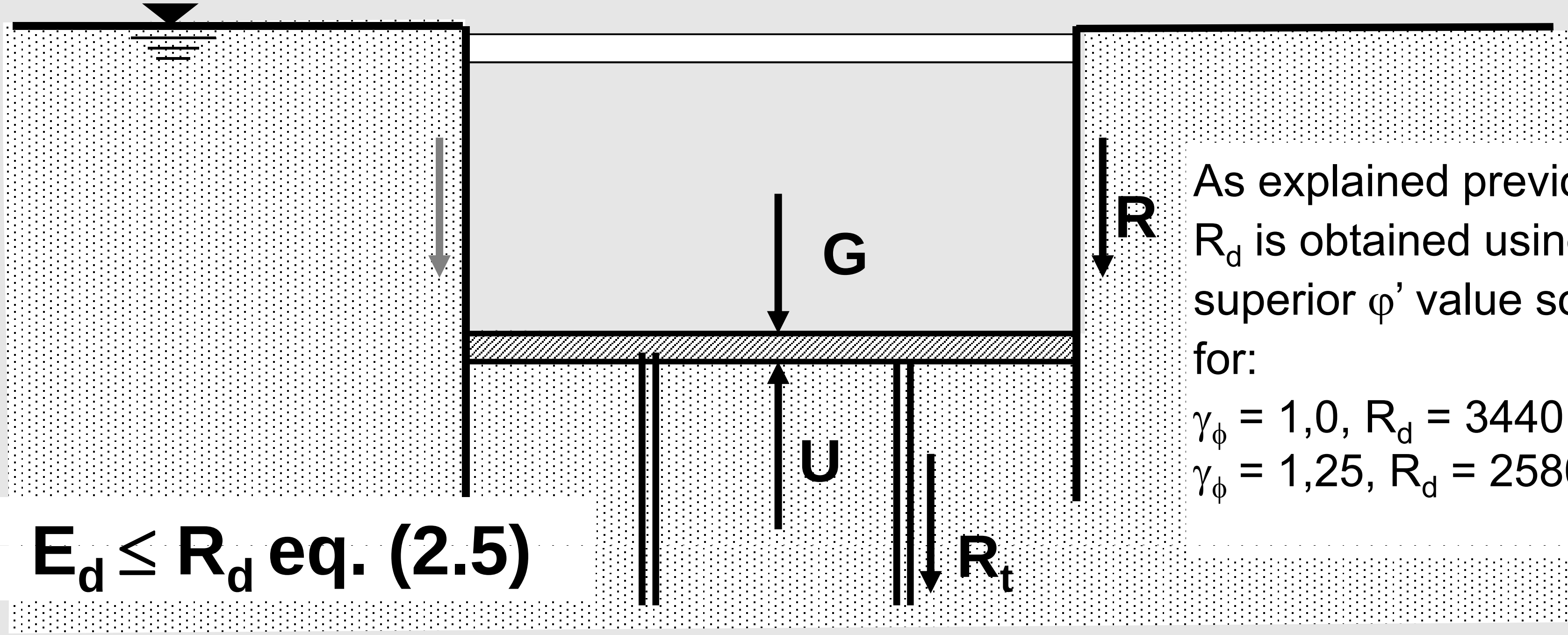
Pile design (GEO) for verification of failure by uplift



Selected:

3 Piles L = 10 m

Irish pile design for GEO verification of uplift failure



As explained previously, R_d is obtained using the superior φ' value so that for:

γ_ϕ = 1,0, R_d = 3440 kN

γ_ϕ = 1,25, R_d = 2580 kN

$$\mathbf{E_d \leq R_d} \text{ eq. (2.5)}$$

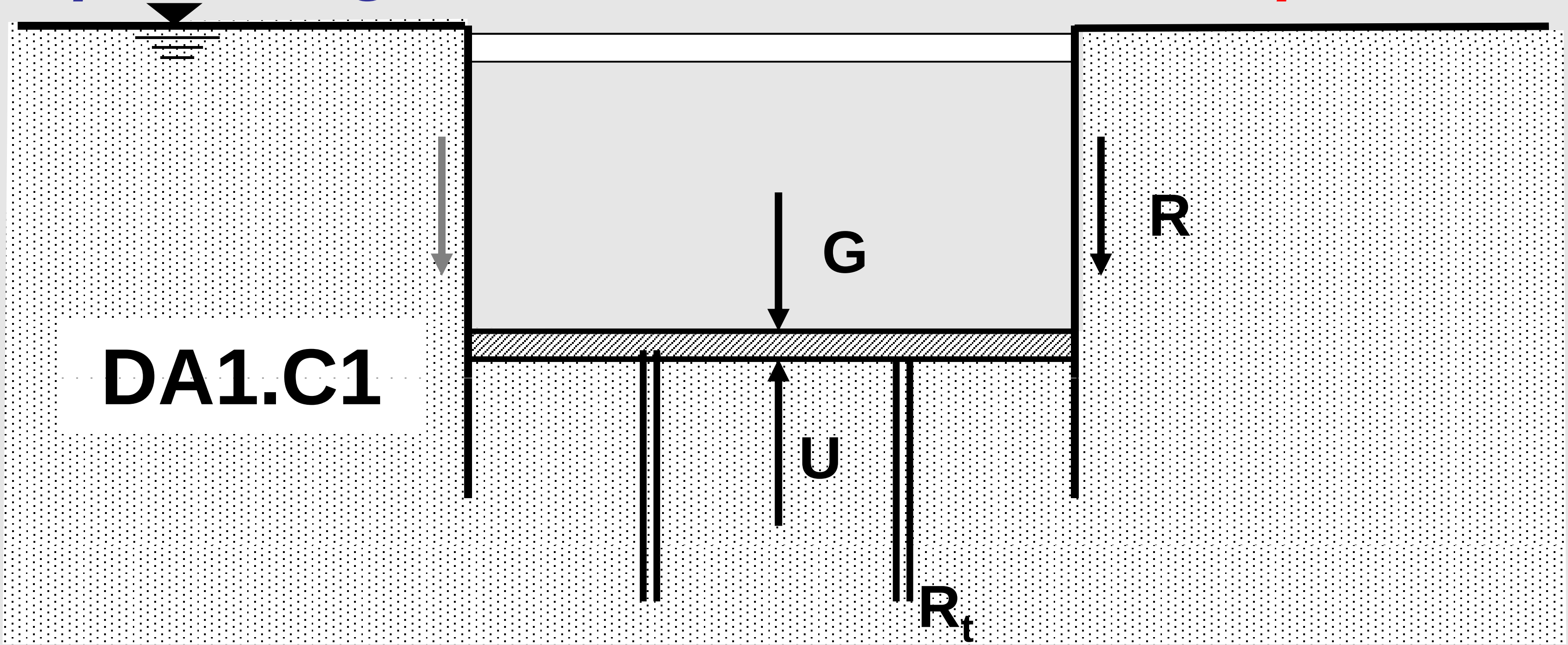
$$E_d = U_k \cdot \gamma_G - G_k \cdot \gamma_{G,inf} = 5000 \cdot \gamma_G - 2253 \cdot \gamma_{G;inf}$$

$$R_{t,d} = R_{t,k} / \gamma_{s;t} + R_d = L_{tot} \cdot q_{s,k} \cdot \pi \cdot D / \gamma_{s;t} + R_d$$

$$= L_{tot} \cdot 35 \cdot \pi \cdot 0.5 / \gamma_{s;t} + R_d = L_{tot} \cdot 54.98 / \gamma_{s;t} + R_d$$

Hence require: $L_{tot} \geq \gamma_{s;t} (5000 \cdot \gamma_G - 2253 \cdot \gamma_{G;inf} - R_d) / 54.98$

Irish pile design for GEO verification of uplift failure

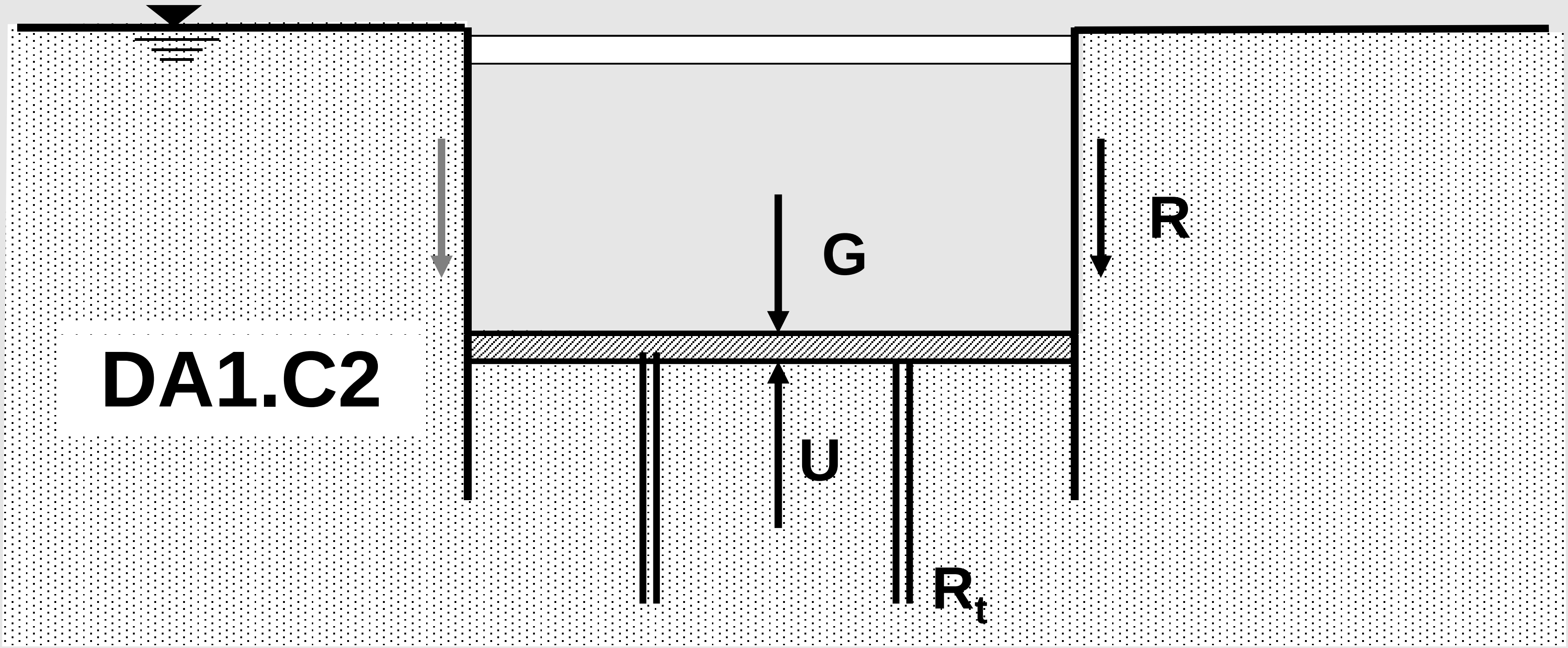


$$L_{tot} \geq 1.25 \cdot (5000 \cdot 1.35 - 2253 \cdot 1.0 - 3440) / 54.98$$

$$L_{tot} = 24.0$$

Hence, for 3 piles, each should be **8 m long**

Irish pile design for verification of GEO uplift failure

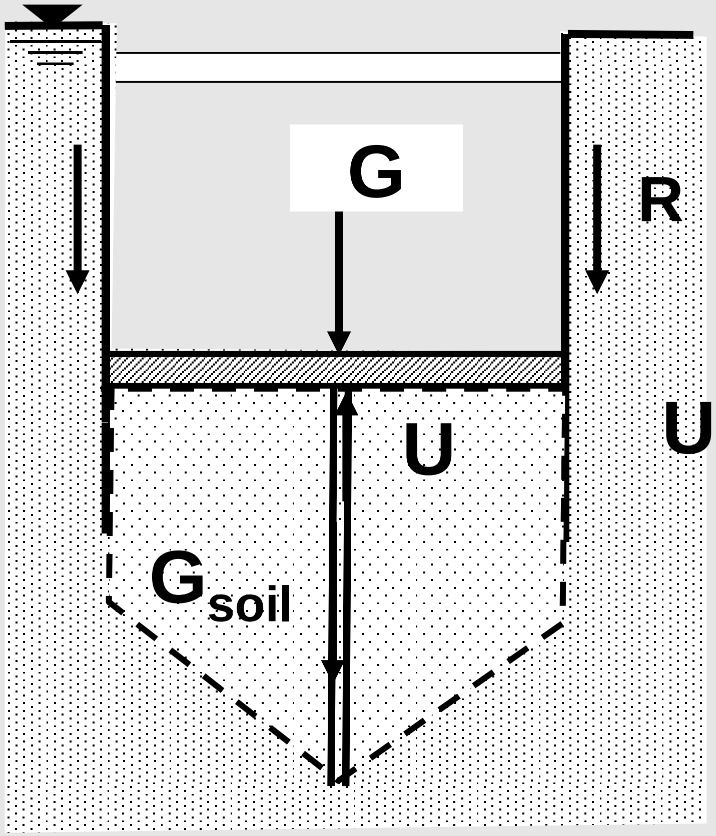


$L_{tot} \geq$ **1.6**·(5000 · **1,0** – 2253 · **1.0** – 2580) / 54,98 **= 4.9m,**

L_{tot} = 4.9m, i.e. for 3 piles, each should be 1.6 m long. **Hence design length is 8 m**

NOTE: DA1.C1 controls the design not DA1.C2 due to large balancing forces

Verification of uplift of structure + ground block containing the piles

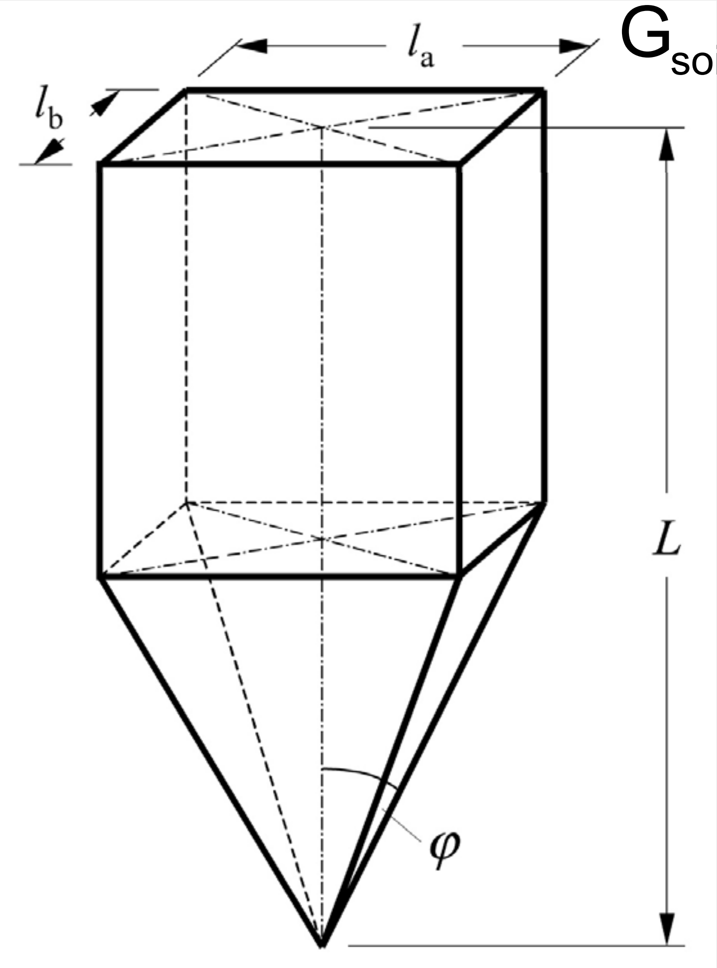


$$V_{dst,d} \leq G_{stb;d} + R_d \qquad (2.8)$$

$$U_d \leq G_d + G_{soil,d} + R_d$$

$$U_k \cdot \gamma_{G,dst} \leq (G_k + G_{soil,k} + R_k) \cdot \gamma_{G,stb}$$

Determination of $G_{soil,k}$ according to DIN 1054, 8.5.4



$$G_{soil,k} = n \cdot \left[l_a \cdot l_b \left(L - 1/3 \cdot \sqrt{l_a^2 + l_b^2} \cdot \cot\varphi\right)\right] \cdot \eta \cdot \gamma'$$

N: number of piles, L = length of piles

l_a = 5,0 m greater grid distance piles,

l_b = 3,33 m smaller grid distance piles,

γ' = 10,0 kN/m³ submerged weight soil

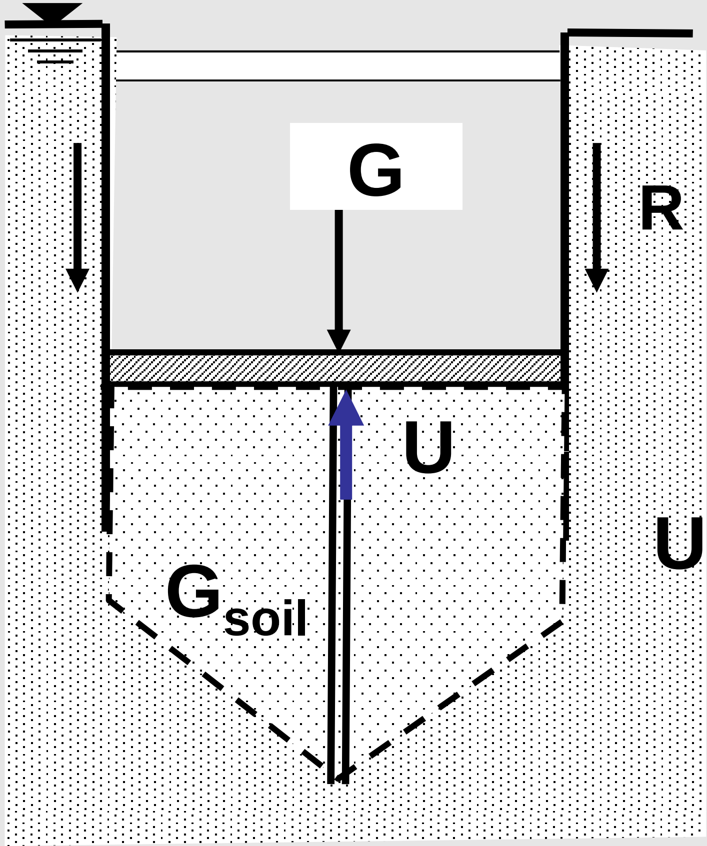
η = 0,80 model factor for the weight.

$$G_{soil,k} = 3 \cdot \{5{,}0 \cdot 3{,}33 \cdot (10 - 1/3 \sqrt{5{,}0^2 + 3{,}33^2} \cot 32{,}5°)\} \cdot 0{,}8 \cdot 10$$

$\mathbf{G_{soil,k} = 2740\ kN}$

Model factor: η = 0,80
according to DIN 1054!

Verification of uplift of structure + ground block containing the piles



$$U_d \leq G_d + R_d + G_{soil,d}$$

$$U_k \cdot \gamma_{G,dst} \leq (G_k + R_k + G_{soil,k}) \cdot \gamma_{G,stb}$$

$$5000 \leq 6906 \text{ kN}$$

Worked example:
failure by hydraulic heave HYD

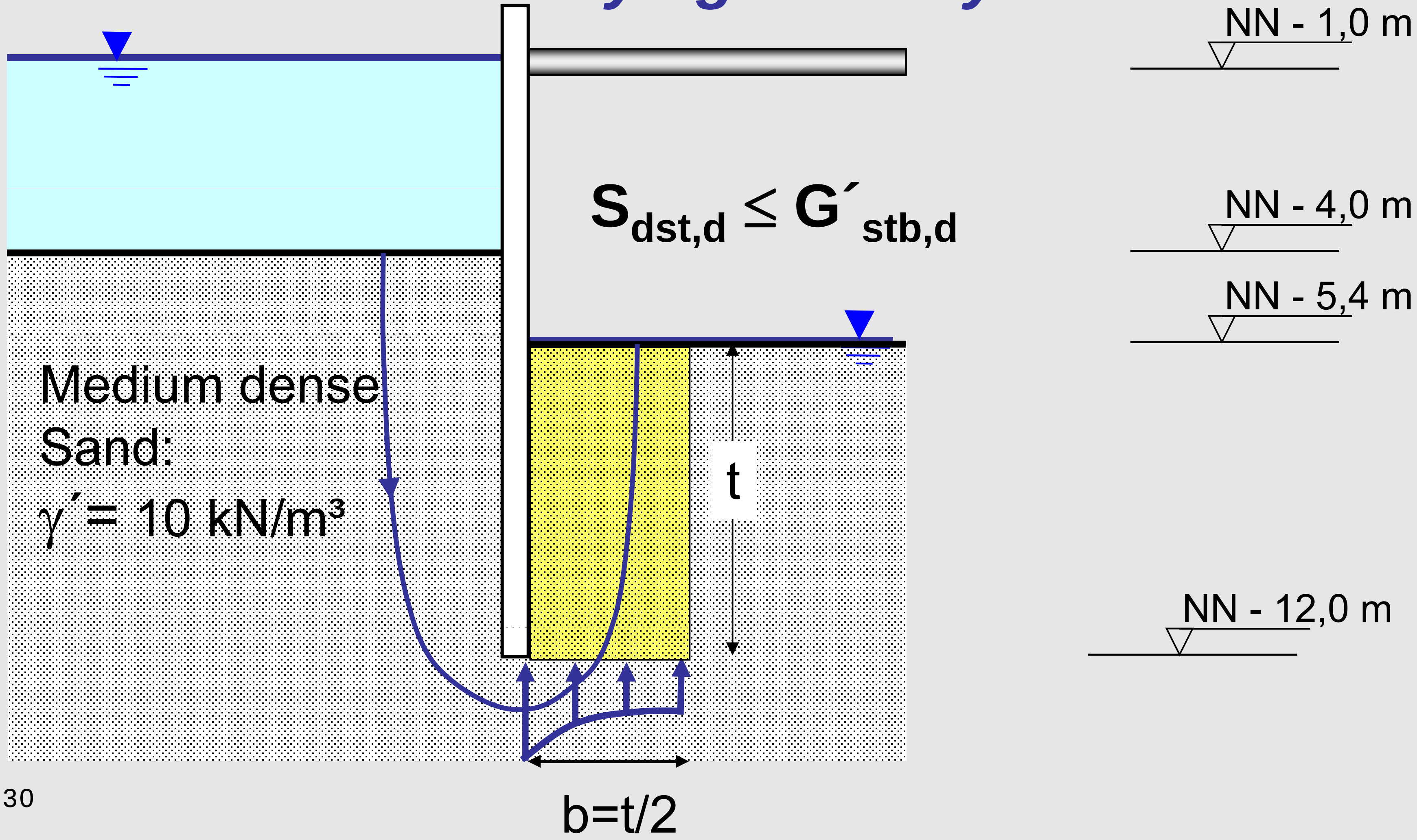
2.4.7.5 Verification of failure by heave

(1)P When considering a limit state of failure due to heave by seepage of water in the ground (HYD, see 10.3), it shall be verified, for every relevant soil column, that the design value of the destabilising total pore water pressure ($u_{dst;d}$) at the bottom of the column, or the design value of the seepage force ($S_{dst;d}$) in the column is less than or equal to the stabilising total vertical stress ($\sigma_{stb;d}$) at the bottom of the column, or the submerged weight ($G'_{stb;d}$) of the same column:

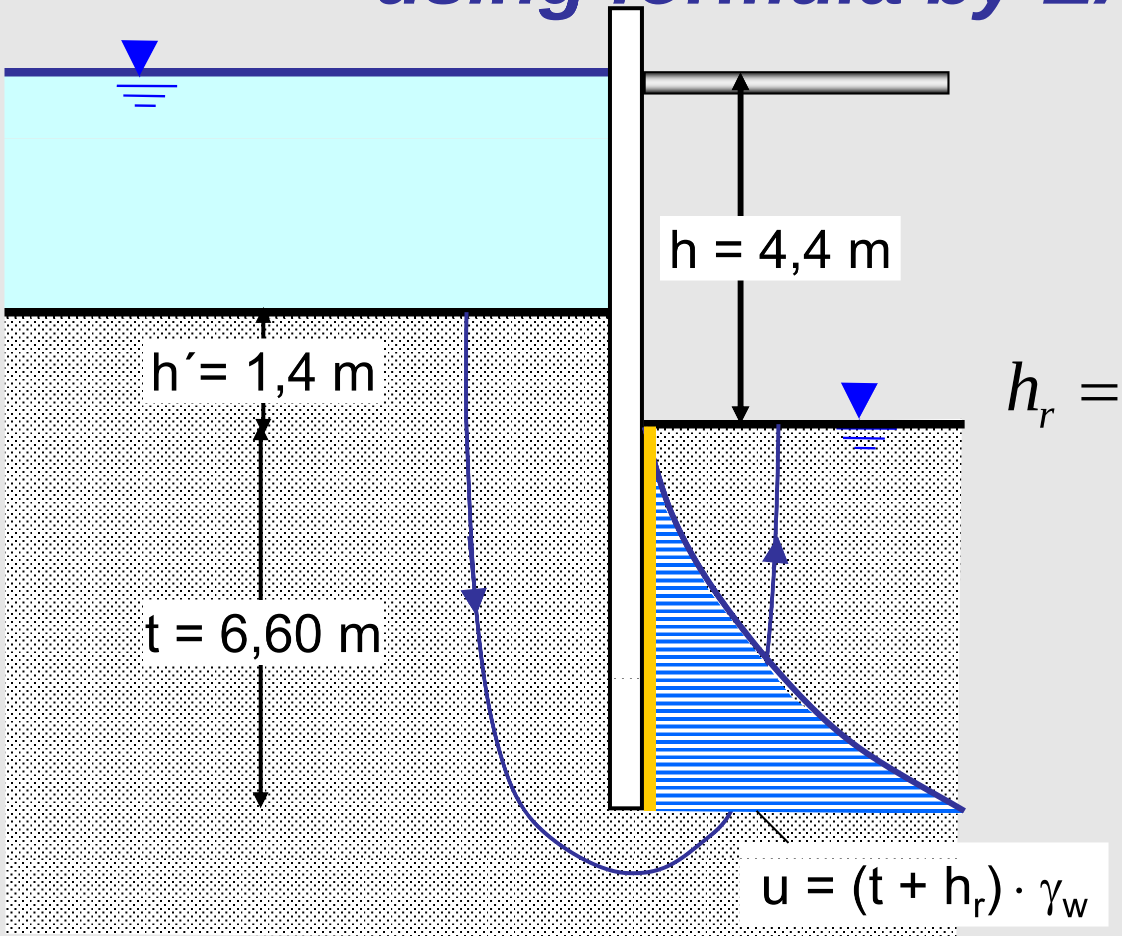
$$u_{dst;d} \leq \sigma_{stb;d} \qquad (2.9a)$$

$$S_{dst;d} \leq G'_{stb;d} \qquad (2.9b)$$

Verification of safety against hydraulic heave



Verification of safety against hydraulic heave using formula by EAU

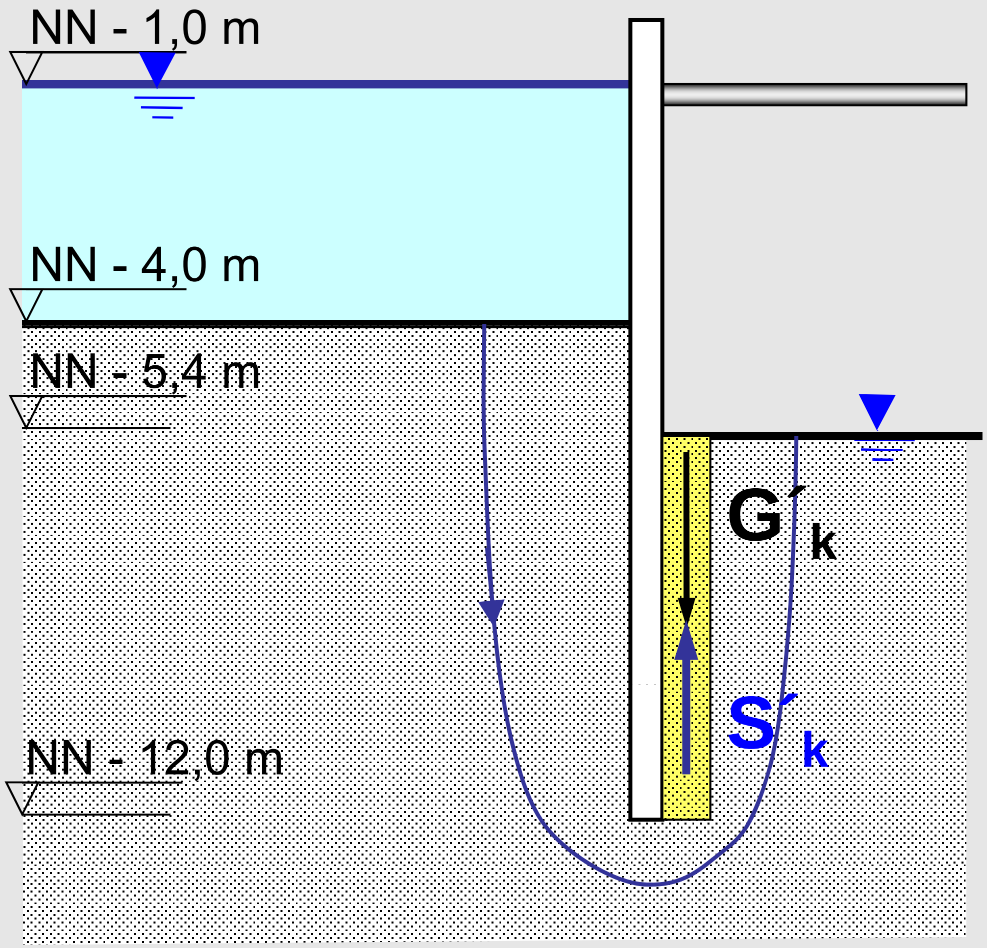


$$h_r = \frac{h}{1+\sqrt[3]{\frac{h'}{t}+1}}$$

$$h_r = \frac{4,4}{1+\sqrt[3]{\frac{1,4}{6,60}+1}} = 2,13\text{ m}$$

$$i = h_r / t = 0,32$$

Verification of safety against hydraulic heave



Seepage force S_k:

$$S_k = i \cdot \gamma_W \cdot V$$

Effective self weight of the soil column G'_k:

$$G'_k = \gamma' \cdot V$$

HYD Ulimate limit state:

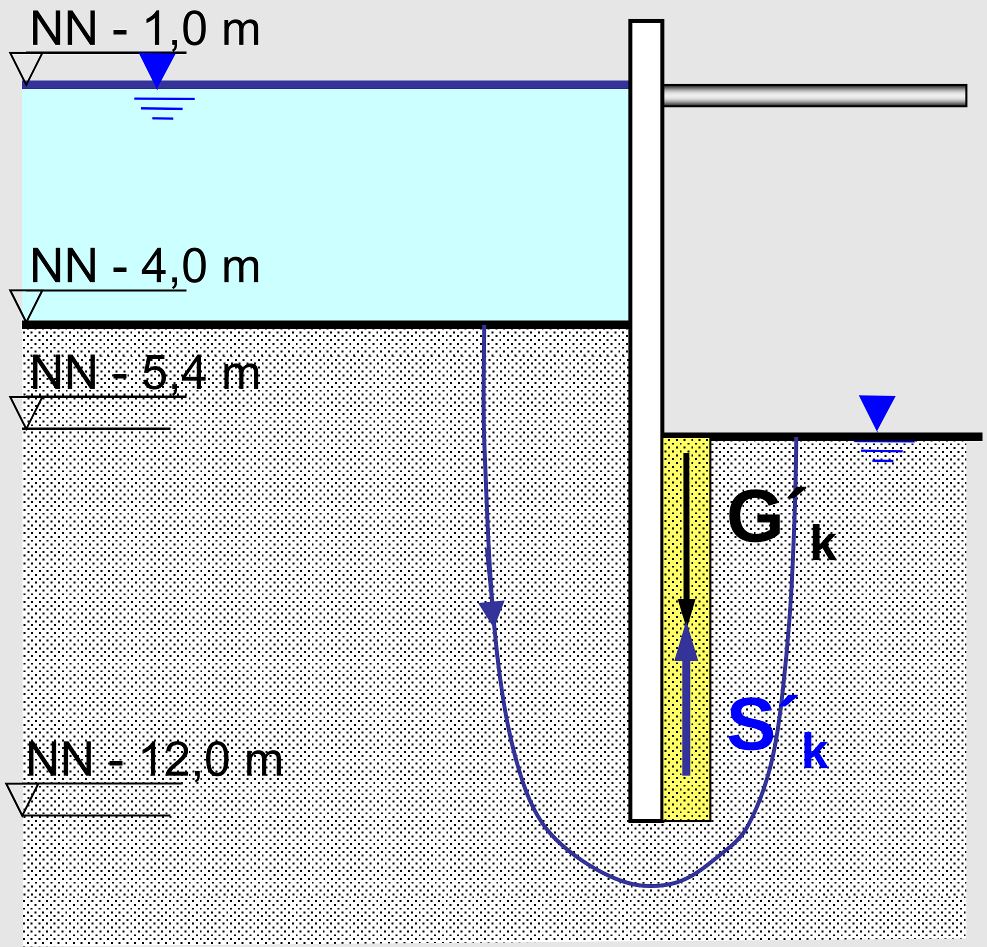
$$S_k \cdot \gamma_{dst} \leq G'_k \cdot \gamma_{G,stb}$$

Verification of safety against hydraulic heave

Table A.17 - Partial factors on actions (γ_F)

Action	Symbol	Value
permanent unfavourable[a] favourable[b]	$\gamma_{G;dst}$ $\gamma_{G;stb}$	1.35 0.90
variable unfavourable[a]	$\gamma_{G;stb}$	1.50
[a] destabilising; [b] stabilising		

Verification of safety against hydraulic heave



Seepage force S_k:

$$S_k = i \cdot \gamma_W \cdot V$$

Effective self weight of the soil column G'_k:

$$G'_k = \gamma' \cdot V$$

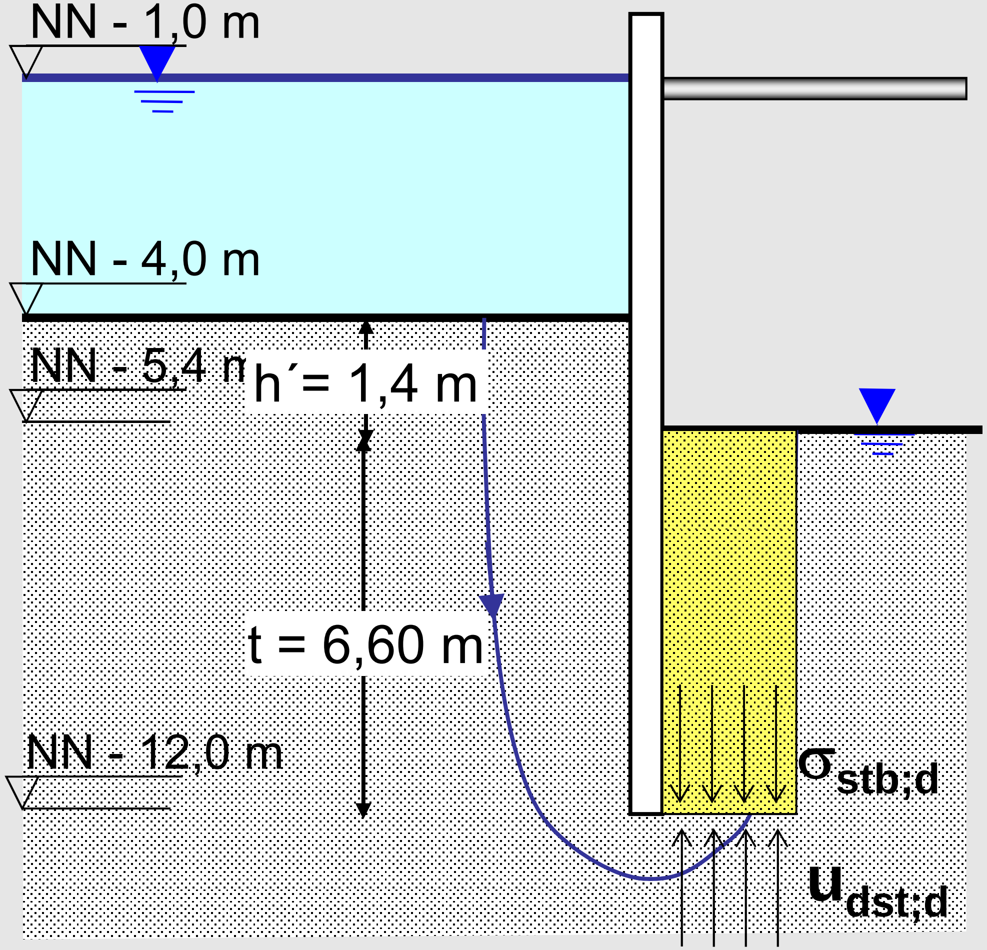
HYD Ulimate limit state:

$$S_k \cdot \gamma_{dst} \leq G'_k \cdot \gamma_{G,stb}$$

$$0.32 \cdot 10 \cdot 1.35 \leq 10 \cdot 0.90$$

$$\mathbf{4.32 \leq 9.0}$$

Safety against hydraulic heave: eq. 2.9b



$$u_{dst;d} \leq \sigma_{stb;d}$$

$u_k = (t + h_r) \cdot \gamma_w$

$h_r = 2,13m$

$u_k = (6.60+2.13)\cdot 10$

$u_k = 87.3$ kN/m²

$\sigma_{stb;k} = t\cdot(\gamma' + \gamma_w)$

$\sigma_{stb;k} = 6.60 \cdot 20$

$\sigma_{stb;k} = 132$ kN/m²

$u_k \cdot \gamma_{G,dst} \leq \sigma_{stb;k} \cdot \gamma_{G,stb}$

$87.3 \cdot 1.35 \leq 132 \cdot 0.90$

$117.9 \leq 118.8$

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Geotechnical design with worked examples

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