Verification Analysis of the Gravity Wall

Program: Gravity Wall
File: Demo_vm_en_01.gtz

In this verification manual you will find hand-made verification analysis calculations of gravity wall in permanent and seismic design situations. The results of the hand-made calculations are compared with the results from the GEO5 – Gravity Wall program.

Terms of Reference:

In Figure 1, an example of a gravity wall with inclined footing bottom in 1:10 inclination is shown. The earth body is comprised of two soil layers and the terrain is adjusted in 1:10 inclination. The top layer of the earth body (depth 1.5 m) is formed of sandy silt (MS). The lower layer of the earth body is formed of clayey sand (SC), which is at the front face of the wall too. The groundwater table is in the depth of 1.5 m behind the wall and 3.7 m in front of the wall. The properties of soils (effective values) are in Table 1. The gravity wall is made from plain concrete C20/25 with unit weight γ = 23 kN/m^3. A verification analysis of the wall is performed with the help of the theory of limit states.

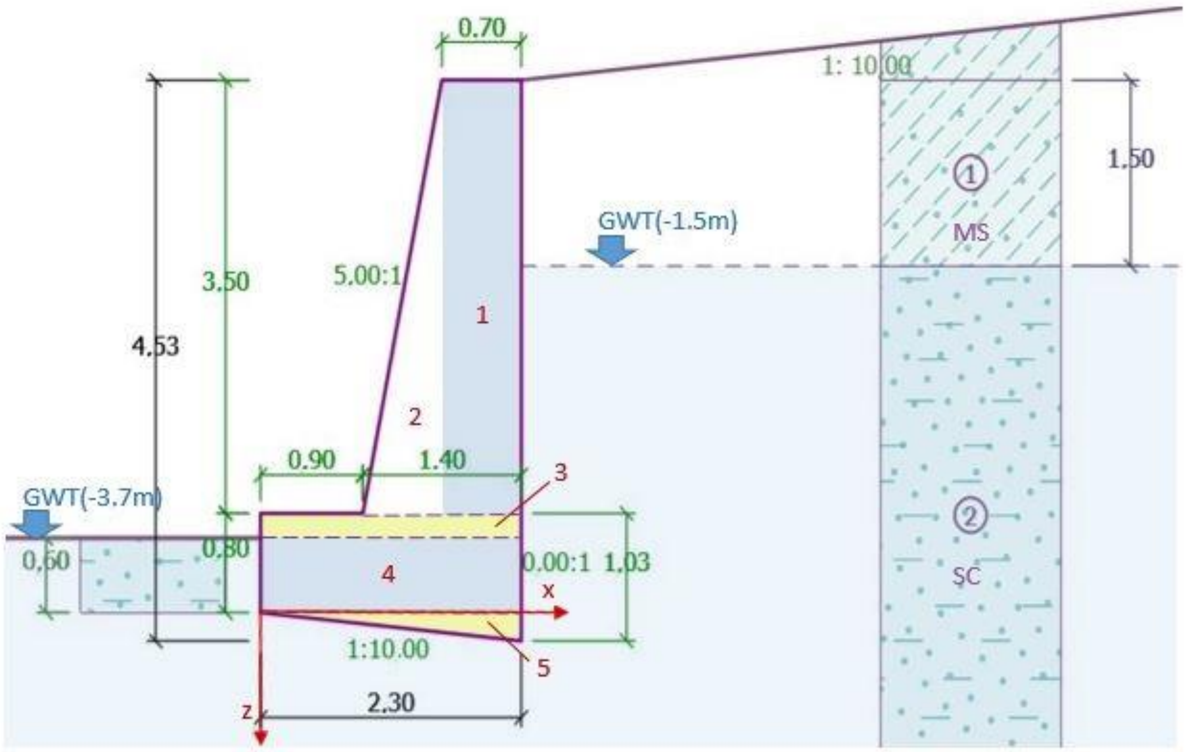

Figure 1 Construction of gravity wall – dimensions

Soil	Unit weight γ [kN/m^3]	Saturated unit weight γ_{sat} [kN/m^3]	Angle of internal friction φ_{ef} [°]	Cohesion of soil c_{ef} [kPa]	Angle of friction struc.-soil δ [°]	Poisson's ratio ν [-]
MS	18.00	20.00	26.50	12.00	15.00	0.35
SC	18.50	20.50	27.00	8.00	15.00	0.35

Table 1 Soil properties – characteristic effective values

The angle of friction and cohesion enter the first phase of the calculation as design values and that's why the soil parameters from Table 1 are reduced with coefficients $\gamma_{m\varphi} = 1.1$ and $\gamma_{mc} = 1.4$. The design values used in calculation are in Table 2.

Soil	Angle of internal friction $\varphi_{ef,d}$ [°]	Cohesion of soil $c_{ef,d}$ [kPa]	Angle of friction struc.-soil δ_d [°]
MS	24.091	8.571	13.636
SC	24.545	5.714	13.636

Table 2 Soil properties – design values

1. The First Stage- Permanent Design Situation

Verification of the Whole Wall

Calculation of the weight force and the centroid of the wall. The wall is divided into 5 parts, which are shown in Figure 1. Parts 4 and 5 are under the groundwater table, therefore the unit weight of concrete is reduced by the unit weight of water γ_w = 10 kN/m^3. Table 3 shows the dimensions of the parts of the wall, their weight forces and centroids.

Part	height h_i [m]	width b_i [m]	Area A_i [m^2]	Part weight γ_i [kN/m^3]	Weight force W_i [kN/m]	Point of action		$G_i \cdot xi$	$G_i \cdot zi$
						x_i [m]	z_i [m]		
1	3.500	0.700	2.450	23	56.350	1.950	-2.550	109.883	-143.693
2	3.500	0.700	1.225	23	28.175	1.367	-1.967	38.506	-55.411
3	0.200	2.300	0.460	23	10.580	1.150	-0.700	12.167	-7.406
4	0.600	2.300	1.380	13	17.940	1.150	-0.300	20.631	-5.382
5	0.230	2.300	0.265	13	3.439	1.533	0.077	5.273	0.264
Total					116.484	-	-	186.460	-211.628

Table 3 Dimensions, weight force and centroids of the individual blocks

- Centroid of the construction:

$$x_t = \frac{\sum_1^5 Wi \cdot xi}{\sum_1^5 Wi} = \frac{186.460}{116.484} = 1.601\ m$$

$$z_t = \frac{\sum_1^5 Wi \cdot zi}{\sum_1^5 Wi} = \frac{-211.628}{116.484} = -1.817\ m$$

Calculation of the front face resistance. The depth of soil in front of the wall is 0.6 m. Pressure at rest is considered.

- Hydraulic gradient:
  (h_w - water tables difference, d_d - seepage path downwards, d_u - seepage path upwards)

$$i = \frac{h_w}{d_d + d_u} = \frac{3.7 - 1.5}{3.03 + 0.6} = 0.606$$

- Coefficient of earth pressure at rest:
  (For cohesive soils the Terzaghi formula for computing of the coefficient of earth pressure at rest K_r is used)

$$K_r = \frac{\nu}{1-\nu} = \frac{0.35}{1-0.35} = 0.538$$

- Unit weight of soil in the area of ascending flow:

$$\gamma = \gamma_{sat} - \gamma_w - \gamma_w \cdot i = 20.5 - 10.0 - 10 \cdot 0.606 = 4.439\ kN/m^3$$

- Vertical normal effective stress σ_z in the footing bottom:

$$\sigma_z = \gamma \cdot h = 4.439 \cdot 0.6 = 2.663\ kPa$$

- Pressure at rest in the footing bottom:

$$\sigma_r = \sigma_z \cdot K_r = 2.663 \cdot 0.538 = 1.433\ kPa$$

- Resultant force of stress at rest S_r :
  (Resultant force S_r acts only in horizontal direction, therefore $S_r = S_{rx}$ and $S_{rz} = 0$)

$$S_r = \frac{1}{2}\sigma_r \cdot h = \frac{1}{2} 1.433 \cdot 0.6 = 0.430\ kN/m$$

- Point of action of the resultant force S_r :

  $x = 0.000\ m$

  $z = -\frac{1}{3}h = -\frac{1}{3}\cdot 0.6 = -0.200\ m$

Calculation of the active pressure. There are two layers of soils in the area, where we solve the active pressure. The structure is therefore divided into two sections, in both of which the geostatic pressure σ_z, the active earth pressure σ_a and the resultant forces S_{a1} and S_{a2} are calculated. The active earth pressure is calculated using Coulomb's theory.

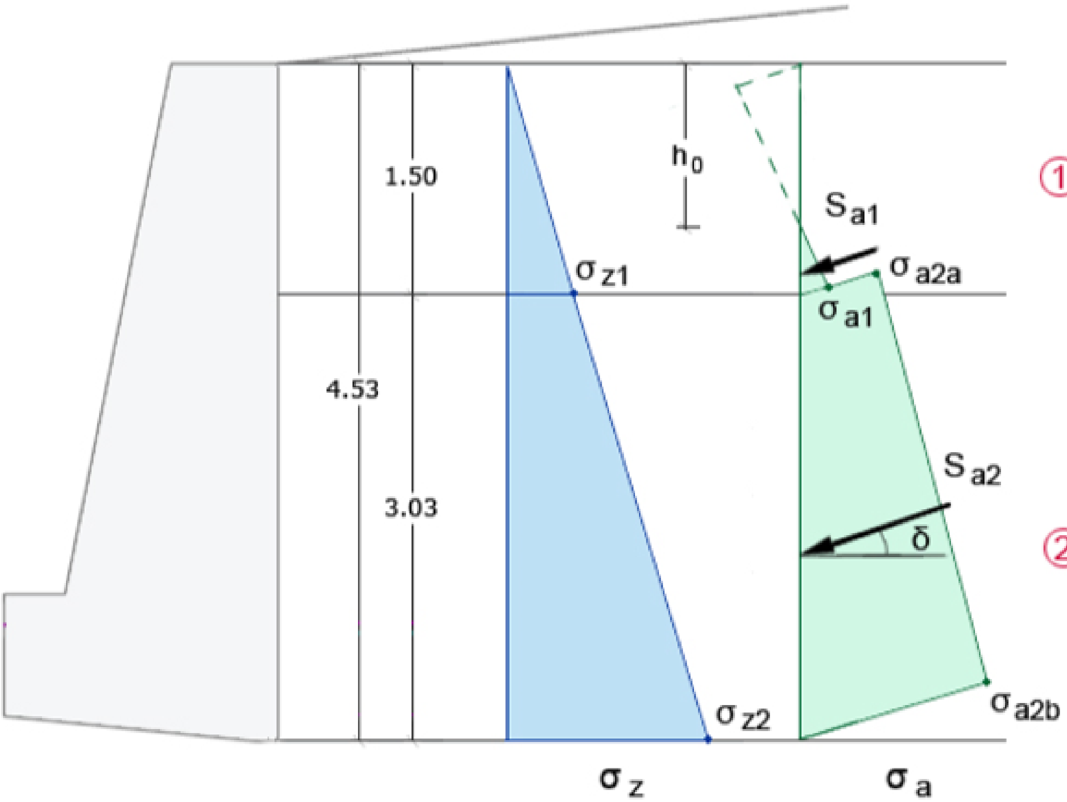

Figure 2 Geostatic pressure σ_z and active pressure σ_a

- Coefficients of active earth pressure in both sections:
  ($\alpha = 0°$ - back face inclination of the structure, $\beta \neq 0°$-inclination of the terrain; design values of soils from Table 2 are used in the calculation)

  K_a - coefficient of active earth pressure

$$K_a = \frac{\cos^2(\varphi-\alpha)}{\cos^2(\alpha)\cdot\cos(\alpha+\delta)\cdot\left(1+\sqrt{\dfrac{\sin(\varphi+\delta)\cdot\sin(\varphi-\beta)}{\cos(\alpha+\delta)\cdot\cos(\alpha-\beta)}}\right)^2}$$

K_{ac} - coefficient of active earth pressure due to cohesion

$$K_{ac} = \frac{\cos(\varphi)\cdot\cos(\beta)\cdot\cos(\delta-\alpha)\cdot\left[1+tg(-\alpha)\cdot tg(\beta)\right]}{1+\sin(\varphi+\delta-\alpha-\beta)}\cdot\frac{1}{\cos(\delta+\alpha)}$$

Calculation for the first section:

$$\beta_1 = \beta = arctg\left(\frac{1}{10}\right) = 5.711°$$

$$K_{a1} = \frac{\cos^2(24.091-0)}{\cos^2(0)\cdot\cos(0+13.636)\cdot\left(1+\sqrt{\frac{\sin(24.091+13.636)\cdot\sin(24.091-5.711)}{\cos(0+13.636)\cdot\cos(0-5.711)}}\right)^2} = 0.4097$$

$$K_{ac1} = \frac{\cos(24.091)\cdot\cos(5.711)\cdot\cos(13.636-0)\cdot\left[1+tg(-0)\cdot tg(5.711)\right]}{1+\sin(24.091+13.636-0-5.711)}\cdot\frac{1}{\cos(13.636+0)} = 0.5936$$

Calculation for the second section:

$$\beta_2 = arctg\left(\frac{\gamma\cdot tg(\beta)}{\gamma_i}\right) = arctg\left(\frac{18.0\cdot tg(5.711)}{18.5}\right) = 5.557°$$

$$K_{a2} = \frac{\cos^2(24.545-0)}{\cos^2(0)\cdot\cos(0+13.636)\cdot\left(1+\sqrt{\frac{\sin(24.545+13.636)\cdot\sin(24.545-5.557)}{\cos(0+13.636)\cdot\cos(0-5.557)}}\right)^2} = 0.4016$$

$$K_{ac2} = \frac{\cos(24.545)\cdot\cos(5.557)\cdot\cos(13.636-0)\cdot\left[1+tg(-0)\cdot tg(5.557)\right]}{1+\sin(24.545+13.636-0-5.557)}\cdot\frac{1}{\cos(13.636+0)} = 0.5882$$

- Unit weight of soil SC in the area of descending flow:

  $$\gamma_2 = \gamma_{sat} - \gamma_w + \gamma_w\cdot i = 20.5 - 10.0 + 10\cdot 0.606 = 16.561\ kN/m^3$$

- Vertical geostatic pressure σ_z in two sections:

  $$\sigma_{z1} = \gamma_1\cdot h_1 = 18.0\cdot 1.5 = 27.000\ kPa$$

  $$\sigma_{z2} = \gamma_1\cdot h_1 + \gamma_2\cdot h_2 = 18.0\cdot 1.5 + 16.561\cdot 3.03 = 77.180\ kPa$$

- Calculation of high in first layer of soil MS, where the active earth pressure is neutral:

  $$h_0 = \frac{2\cdot c_{ef,d1}\cdot K_{ac1}}{\gamma_1\cdot K_{a1}} = \frac{2\cdot 8.571\cdot 0.5936}{18.0\cdot 0.4097} = 1.380\ m$$

- Active earth pressure σ_a in two sections:

  $$\sigma_{a1} = \sigma_{z1}\cdot K_{a1} - 2\cdot c_{ef,d1}\cdot K_{ac1} = 27.00\cdot 0.4097 - 2\cdot 8.571\cdot 0.5936 = 0.886\ kPa$$

$$\sigma_{a2a} = \sigma_{z1} \cdot K_{a2} - 2 \cdot c_{ef,d2} \cdot K_{ac2} = 27.00 \cdot 0.4016 - 2 \cdot 5.714 \cdot 0.5882 = 4.121\,kPa$$

$$\sigma_{a2b} = \sigma_{z2} \cdot K_{a2} - 2 \cdot c_{ef,d2} \cdot K_{ac2} = 77.18 \cdot 0.4016 - 2 \cdot 5.714 \cdot 0.5882 = 24.274\,kPa$$

- Resultant forces of active earth pressure S_{a1}, S_{a2} and vertical and horizontal components:

$$S_{a1} = \frac{1}{2} \cdot \sigma_{a1} \cdot (h_1 - h_0) = \frac{1}{2} \cdot 0.886 \cdot (1.500 - 1.380) = 0.053\,kN/m$$

$$S_{a1,x} = S_{a1} \cdot \cos(\delta) = 0.053 \cdot \cos(13.636) = 0.052\,kN/m$$

$$S_{a1,z} = S_{a1} \cdot \sin(\delta) = 0.053 \cdot \sin(13.636) = 0.013\,kN/m$$

$$S_{a2} = \frac{1}{2} \cdot (\sigma_{a2b} - \sigma_{a2a}) \cdot h_2 + \sigma_{a2a} \cdot h_2 = \frac{1}{2} \cdot (24.274 - 4.121) \cdot 3.03 + 4.121 \cdot 3.03 = 43.018\,kN/m$$

$$S_{a2,x} = S_{a2} \cdot \cos(\delta) = 43.018 \cdot \cos(13.636) = 41.806\,kN/m$$

$$S_{a2,z} = S_{a2} \cdot \sin(\delta) = 43.018 \cdot \sin(13.636) = 10.142\,kN/m$$

- Points of action of resultant forces S_{a1} and S_{a2}:

$$x_1 = 2.300\,m$$

$$z_1 = -0.8 - 2.0 - \frac{1.5 - 1.38}{3} = -2.840\,m$$

$$x_2 = 2.300\,m$$

$$z_2 = \frac{4.121 \cdot 3.03 \cdot \left(-\frac{3.03}{2} + 0.23\right) + (24.274 - 4.121)\frac{3.03}{2} \cdot \left(-\frac{3.03}{3} + 0.23\right)}{4.121 \cdot 3.03 + (24.274 - 4.121) \cdot \frac{3.03}{2}} = -0.927\,m$$

- Total resultant force of active earth pressure S_a:

$$S_{ax} = S_{a1,x} + S_{a2,x} = 0.052 + 41.806 = 41.858\,kN/m$$

$$S_{az} = S_{a1,z} + S_{a2,z} = 0.013 + 10.142 = 10.155\,kN/m$$

$$S_a = \sqrt{S_{ax}^2 + S_{az}^2} = \sqrt{41.858^2 + 10.155^2} = 43.072\,kN/m$$

- Point of action of total resultant force:

$$x_a = 2.300\ m$$

$$z_a = \frac{\sum_1^2 S_{ai,z} \cdot z_i}{\sum_1^2 S_{ai,z}} = \frac{0.013 \cdot (-2.840) + 10.142 \cdot (-0.927)}{10.155} = -0.929\ m$$

Calculation of the water pressure. The heel of the structure is sunken in a permeable subsoil, which allows free water flow below the structure. Therefore, the hydrodynamic pressure must be considered and its resultant force is calculated as shown in Figure 3. The area of the hydrodynamic pressure is divided into two sections.

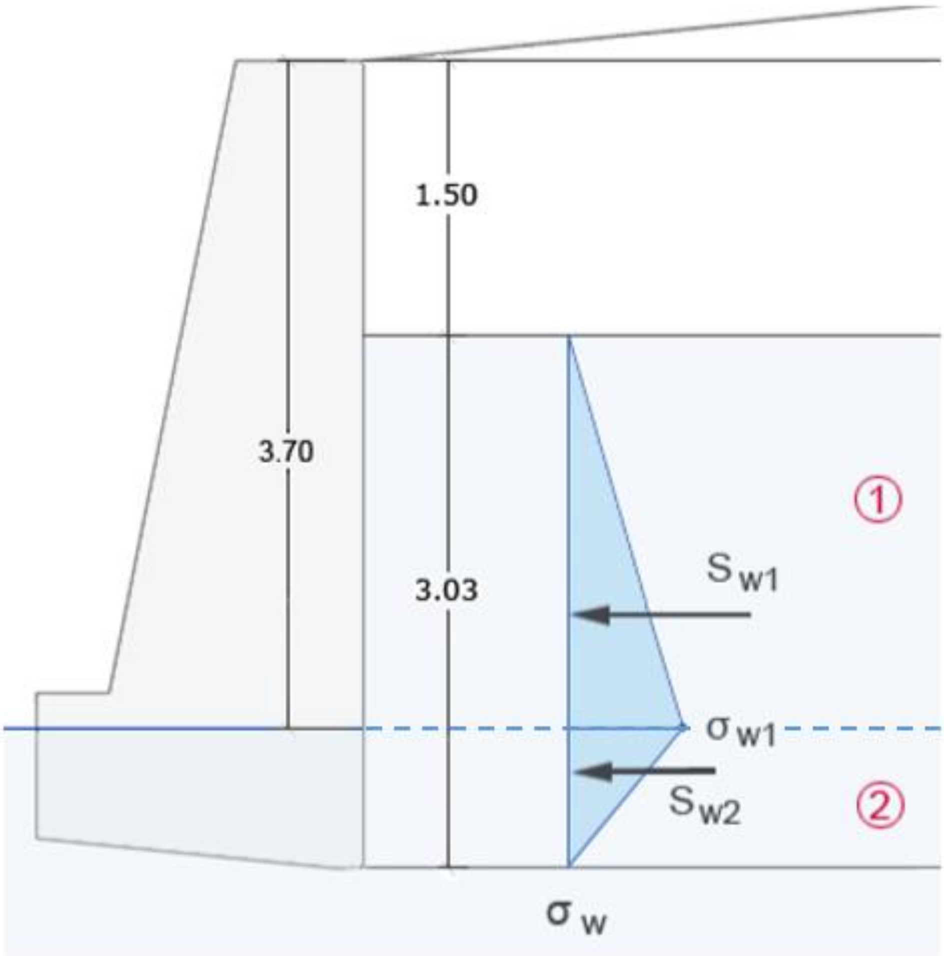

Figure 3 Hydrodynamic pressure σ_w

- Horizontal water pressure σ_w at interface of section 1 and section 2 (depth 3.7 m):

  $\sigma_w = \gamma_w \cdot (3.7 - 1.5) = 10 \cdot 2.2 = 22.000\ kPa$

- Resultant force of water pressure S_w in two sections:

  $$S_{w1} = \frac{1}{2} \cdot \sigma_w \cdot h_{w1} = \frac{1}{2} \cdot 22.000 \cdot 2.2 = 24.200\ kN/m$$

$$S_{w2} = \frac{1}{2} \cdot \sigma_w \cdot h_{w2} = \frac{1}{2} \cdot 22.000 \cdot 0.83 = 9.130\ kN/m$$

- Points of action of resultant forces:

$$x_1 = 2.300\ m$$

$$z_1 = -0.6 - \frac{2.2}{3} = -1.333\ m$$

$$x_2 = 2.300\ m$$

$$z_2 = -0.6 + \left(\frac{0.6 + 0.23}{3}\right) = -0.323\ m$$

- Total resultant force of water pressure S_w:

$$S_w = \sum_1^2 S_{w,i} = 24.200 + 9.130 = 33.330\ kN/m$$

- Point of action of resultant force S_w:

$$x_w = 2.300\ m$$

$$z_w = \frac{\sum_1^2 S_{wi} \cdot z_i}{\sum_1^2 S_{wi}} = \frac{24.2 \cdot (-1.333) + 9.13 \cdot (-0.323)}{33.33} = -1.056\ m$$

Checking for overturning stability. The moments calculated in the analysis rotate about the origin of the coordinate system (left bottom corner of the structure). Resisting moment M_{res} and overturning moment M_{ovr} are calculated for verification.

- Calculation of resisting moment M_{res} and its reduction by coefficient $\gamma_S = 1.1$:

$$M_{res} = W \cdot r_1 + S_{az} \cdot r2 = 116.484 \cdot 1.601 + 10.155 \cdot 2.3 = 209.847\ kNm/m$$

$$\frac{M_{res}}{\gamma_S} = \frac{209.847}{1.1} = 190.770\ kNm/m$$

Result from the GEO5 – Gravity Wall program: $M_{res} = 190.74\ kNm/m$

- Calculation of overturning moment M_{ovr}:

$$M_{ovr} = -0.430 \cdot 0.2 + 41.858 \cdot 0.929 + 33.33 \cdot 1.056 = 73.997\ kNm/m$$

Result from the GEO5 – Gravity Wall program: $M_{ovr} = 74.02\ kNm/m$

- Usage:

$$V_u = \frac{M_{ovr}}{M_{res}} \cdot 100 = \frac{73.997}{190.770} \cdot 100 = 38.8\,\%$$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 38.8\,\%$ **, SATISFACTORY**

Checking for slip. Slip in the inclined footing bottom (Figure 4).

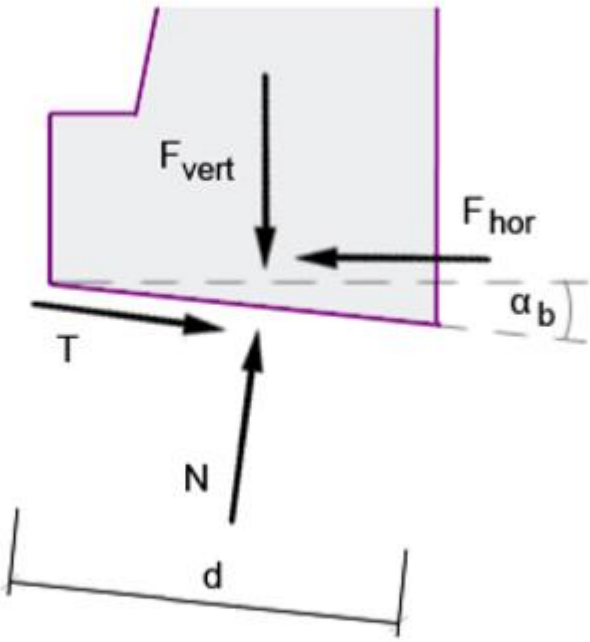

Figure 4 Forces acting in the footing bottom

- Total vertical and horizontal forces F_{ver} and F_{hor} :

$$F_{ver} = 116.484 + 10.155 = 126.639\ kN/m$$

$$F_{hor} = -0.43 + 41.858 + 33.33 = 74.758\ kN/m$$

- Normal force N :

$$\alpha_b = 5.711\,°$$

$$N = F_{ver} \cdot \cos(\alpha_b) + F_{hor} \cdot \sin(\alpha_b) = 126.639 \cdot coc(5.711) + 74.758 \cdot \sin(5.711) = 133.450\ kN/m$$

- Shear force T :

$$T = -F_{ver} \cdot \sin(\alpha_b) + F_{hor} \cdot \cos(\alpha_b) = -126.639 \cdot \sin(5.711) + 74.758 \cdot \cos(5.711) = 61.785\ kN/m$$

- Eccentricity of normal force:

d - inclined width of footing bottom

e_{alw} - maximal allowable eccentricity

$$d = \frac{2.3}{\cos(\alpha_b)} = \frac{2.3}{\cos(5{,}711)} = 2.311\ m$$

$$e = \frac{M_{ovr} - M_{res} + \frac{N \cdot d}{2}}{N} = \frac{73.997 - 209.847 + \frac{133.450 \cdot 2.311}{2}}{133.450} = 0.138\ m$$

In the program, eccentricity is calculated as a ratio.

$$e_{ratio} = \frac{e}{d} = \frac{0.138}{2.311} = 0.060$$

$e_{alw} = 0.333 \quad \geq \quad e_{ratio} = 0.060$, SATISFACTORY

- Resisting horizontal force H_{res} and its reduction by coefficient $\gamma_S = 1.1$:

  μ - reduction coefficient of contact base - soil

  $\mu = 1.0$ (without reduction)

  F_{res} - resisting force

  $F_{res} = 0\ kN$

  $$H_{res} = \left(N \cdot tg\varphi_d + \frac{c_d \cdot (d - 2 \cdot e)}{\mu} \right) + F_{res} = \left(133.450 \cdot tg(24.545) + \frac{5.714 \cdot (2.311 - 2 \cdot 0.138)}{1.0} \right) + 0$$

  $$H_{res} = 72.571\ kN/m$$

  $$\frac{H_{res}}{\gamma_S} = \frac{72.571}{1.1} = 65.974\ kN/m$$

  Result from the GEO5 – Gravity Wall program: $H_{res} = 65.98\ kNm/m$

- Acting horizontal force H_{act}:

  $$H_{act} = T = 61.785\ kN/m$$

  Result from the GEO5 – Gravity Wall program: $H_{act} = 61.79\ kNm/m$

- Usage:

  $V_u = \frac{H_{act}}{H_{res}} \cdot 100 = \frac{61.785}{65.974} \cdot 100 = 93.7\ \%$, SATISFACTORY

  Result from the GEO5 – Gravity Wall program: $V_u = 93.6\ \%$**, SATISFACTORY**

Bearing Capacity of the Foundation Soil

The bearing capacity of the foundation sol is set to $R_d = 100\ kPa$, and is compared with the stress in the inclined footing bottom.

- Usage – eccentricity:

$$V_u = \frac{e}{e_{alw}} \cdot 100 = \frac{0{,}060}{0{,}333} \cdot 100 = 18{,}0\ \%$$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 18.0\ \%$ **, SATISFACTORY**

- Stress in the footing bottom σ :

$$\sigma = \frac{N}{d - 2 \cdot e} = \frac{133.450}{2.311 - 2 \cdot 0.138} = 65.577\ kPa$$

Result from the GEO5 – Gravity Wall program: $\sigma = 65.57\ kPa$

- Usage:

$$V_u = \frac{\sigma}{R_d} \cdot 100 = \frac{65.577}{100} \cdot 100 = 65.6\ \%$$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 65.6\ \%$ **, SATISFACTORY**

Dimensioning – Wall Stem Check

In this example, a cross-section in the level of x-axis in Figure 5 is verified. The verified cross-section is made from plain concrete C 20/25 (characteristic cylindrical strength of concrete in compression $f_{ck} = 20000\ kPa$, characteristic strength of concrete in tension $f_{ctm} = 2200\ kPa$) with height $h = 1.40\ m$ and width $b = 1.00\ m$. The verification of a cross-section made from plain concrete is realized in accordance with EN 1992-1-1.

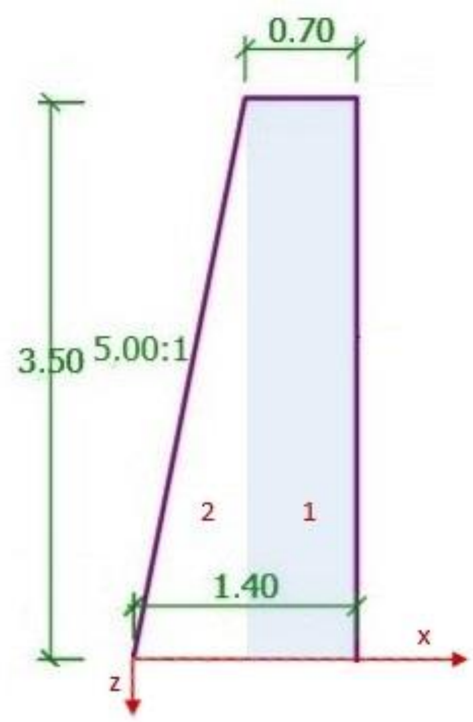

Figure 5 Dimensioning – wall stem check, cross-section

- Calculation of the weight force and the centroid of the wall:

  $$W = 23 \cdot (0.7 \cdot 3.5 + \frac{1}{2} \cdot 0.7 \cdot 3.5) = 84.525\ kN/m$$

  $$x_t = \frac{23 \cdot \left(0.7 \cdot 3.5 \cdot \left(\frac{0.7}{2} + 0.7\right) + \frac{1}{2} \cdot 0.7 \cdot 3.5 \cdot \frac{2 \cdot 0.7}{3}\right)}{84.525} = 0.856\ m$$

  $$z_t = \frac{23 \cdot \left(0.7 \cdot 3.5 \cdot \left(-\frac{3.5}{2}\right) + \frac{1}{2} \cdot 0.7 \cdot 3.5 \cdot \left(-\frac{3.5}{3}\right)\right)}{84.525} = -1.556\ m$$

Calculation of the active earth pressure. The area behind the evaluated part of the construction is divided into two sections. In the first section, the active pressure is the same as in the analysis of the whole wall. The centroids of all forces must be recalculated.

- Vertical geostatic stress σ_{z2} at the end of the second section:

  $$\sigma_{z2} = \sigma_{z1} + \gamma_2 \cdot h_2 = 27.0 + 16.561 \cdot 2.0 = 60.122\ kPa$$

- Active earth pressure σ_{a2b} at the end of the second section:

  $$\sigma_{a2b} = 0.4016 \cdot 60.122 - 2 \cdot 5.714 \cdot 0.5882 = 17.423\ kPa$$

- Resultant force of active earth pressure S_{a2} and vertical and horizontal component:
  (Resultant force S_{a1} at the beginning is the same)

$$S_{a2} = \frac{1}{2} \cdot (17.423 - 4.121) \cdot 2.0 + 4.121 \cdot 2.0 = 21.544\ kN/m$$

$$S_{a2,x} = S_{a2} \cdot \cos(\delta) = 21.544 \cdot \cos(13.636) = 20.937\ kN/m$$

$$S_{a2,z} = S_{a2} \cdot \sin(\delta) = 21.544 \cdot \sin(13.636) = 5.079\ kN/m$$

- Calculation of points of action:

$$x_1 = 1.400\ m$$

$$z_1 = -\frac{1}{3}(1.50 - 1.38) - 2 = -2.040\ m$$

$$x_2 = 1.400\ m$$

$$z_2 = \frac{4.121 \cdot 2.00 \cdot \left(-\frac{2.00}{2}\right) + (17.423 - 4.121)\frac{2.00}{2} \cdot \left(-\frac{2.00}{3}\right)}{4.121 \cdot 2.00 + (17.423 - 4.121) \cdot \frac{2{,}00}{2}} = -0.794\ m$$

- Total resultant force of active earth pressure S_a and horizontal and vertical component:

$$S_{ax} = S_{a1,x} + S_{a2,x} = 0.052 + 20.937 = 20.989\ kN/m$$

$$S_{az} = S_{a1,z} + S_{a2,z} = 0.013 + 5.079 = 5.092\ kN/m$$

$$S_a = \sqrt{S_{ax}^{\ 2} + S_{az}^{\ 2}} = \sqrt{20.989^2 + 5.092^2} = 21.598\ kN/m$$

- Point of action of resultant force S_a:

$$x_a = 1.400\ m$$

$$z_a = \frac{0.052 \cdot (-2.840 + 0.800) + 20.937 \cdot (-0.794)}{0.052 + 20.937} = -0.797\ m$$

Calculation of the water pressure. Water pressure becomes higher with the increasing depth.

- Horizontal water pressure σ_w in depth of 3.5 m under the surface of the adjusted terrain:

$$\sigma_w = \gamma_w \cdot (3.5 - 1.5) = 10 \cdot 2.0 = 20.000\ kPa$$

- Resultant force of water pressure S_w:

$$S_w = \frac{1}{2} \cdot \sigma_w \cdot h_w = \frac{1}{2} \cdot 20.000 \cdot 2.0 = 20.000\ kN/m$$

- Point of action of resultant force S_w:

$$x_1 = 1.400\ m$$

$$z_1 = -\frac{1}{3} \cdot 2{,}0 = -0.667\ m$$

Verification of the shear strength. The design shear force, design normal force, design bending moment and shear strength of the cross-section are calculated. The design bending moment rotates about the middle of the verified cross-section.

- Design shear force V_{Ed}:

$$V_{Ed} = S_w + S_{ax} = 20.000 + 20.989 = 40.989\ kN/m$$

Result from the GEO5 – Gravity Wall program: $V_{Ed} = 40.94\ kN/m$

- Design normal force N_{Ed}:

$$N_{Ed} = S_{az} + W = 5.092 + 84.525 = 89.617\ kN/m$$

Result from the GEO5 – Gravity Wall program: $N_{Ed} = 89.57\ kN/m$

- Design bending moment M_{Ed}:

$$M_{Ed} = -W \cdot r_1 - S_{az} \cdot r_2 + S_{ax} \cdot r_3 + S_w \cdot r_4$$

$$M_{Ed} = -84.525 \cdot (0.856 - 0.700) - 5.092 \cdot 0.700 + 20.989 \cdot 0.797 + 20.000 \cdot 0.667 = 13.311\ kNm/m$$

Result from the GEO5 – Gravity Wall program: $M_{Ed} = 13.32\ kNm/m$

- Calculation of the area of compressed concrete A_{cc}:

  Determining the compressed area of concrete is necessary in order to determine the stresses on the front and the rear edges of the verified cross-section. The normal force N_{Ed} makes compressive stress and therefore is considered to be a negative force.

  Stress from the design normal force N_{Ed}:

$$\frac{N}{A} = \frac{N_{Ed}}{A} = \frac{-89.617}{1.00 \cdot 1.40} = -64.012\ kPa$$

  Stress from the design bending moment M_{Ed}:

$$\pm\frac{M}{W}=\pm\frac{M_{Ed}}{W_y}=\frac{13.311}{\frac{1}{6}\cdot 1.00\cdot 1.40^2}=\pm 40.748\ kPa$$

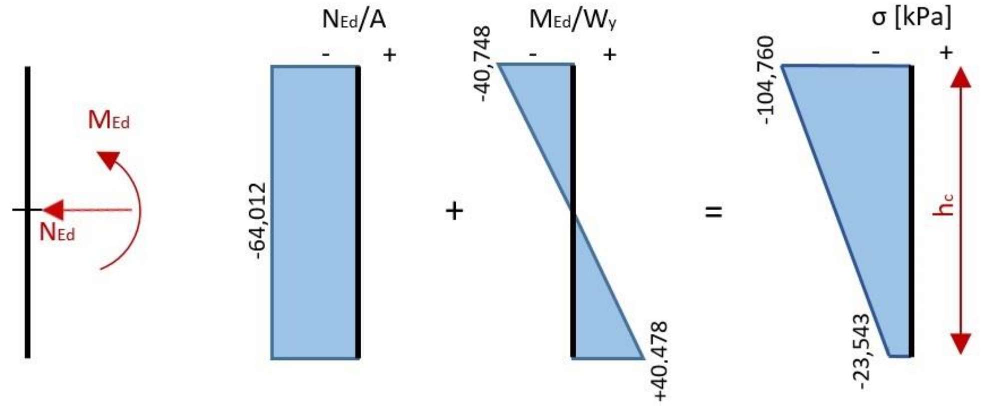

Figure 6 Course of tension on a cross-section of a wall stem

From Figure 6 it can be seen, that the whole area of the cross-section is compressed.

$$A_{cc}=b\,.\,h_c=1.00\cdot 1.40=1.40\ m^2$$

- Stress in cross-section area σ_{cp} :

$$\sigma_{cp}=\frac{N_{Ed}}{A_{cc}}\cdot\frac{1}{1000}=\frac{89.617}{1.400}\cdot\frac{1}{1000}=0.064\ MPa$$

- Design strength of concrete in compression f_{cd} :

$$f_{cd}=\alpha_{cc,pl}\cdot\frac{f_{ck}}{\gamma_c}=0.8\cdot\frac{20.00}{1.5}=10.667\ MPa$$

- Design strength of concrete in tension f_{ctd} :

$f_{ctk,005}$ - lower value of characteristic strength of concrete in tension

$$f_{ctd}=\alpha_{ct,pl}\cdot\frac{f_{ctk,005}}{\gamma_c}=\alpha_{ct,pl}\cdot\frac{0.7\cdot f_{ctm}}{\gamma_c}=0.8\cdot\frac{0.7\cdot 2.20}{1.5}=0.821\ MPa$$

- Limit stress:

$$\sigma_{c,\lim}=f_{cd}-2\cdot\sqrt{f_{ctd}\cdot(f_{cd}+f_{ctd})}=10.667-2\cdot\sqrt{0.821\cdot(10.667+0.821)}=4.525\ MPa$$

- Shear strength f_{cvd} :

$$f_{cvd}=\sqrt{f_{ctd}^2+\sigma_{cp}\cdot f_{ctd}-\left(\frac{\max(0,\sigma_{cp}-\sigma_{c,\lim}}{2}\right)^2}=\sqrt{0.821^2+0.064\cdot 0.821-\left(\frac{\max(0;0.064-4.525}{2}\right)^2}$$

$$f_{cvd}=0.852\ MPa$$

- Design shear strength V_{Rd} :

  $k = 1.5$

  $$V_{Rd} = \frac{f_{cvd} \cdot A_{cc}}{k} \cdot 1000 = \frac{0.852 \cdot 1.4}{1.5} \cdot 1000 = 795.200 \; kN/m$$

  Result from the GEO5 – Gravity Wall program: $V_{Rd} = 795.74 \; kN/m$

- Usage:

  $$V_u = \frac{V_{Ed}}{V_{Rd}} \cdot 100 = \frac{40.989}{795.200} \cdot 100 = 5.2\,\%$$, SATISFACTORY

  Result from the GEO5 – Gravity Wall program: $V_u = 5.1\,\%$ **, SATISFACTORY**

Verification of a cross-section loaded by bending moment and normal force.

- Calculation of eccentricity e :

  $$e = Max\left(abs\left(\frac{M_{Ed}}{N_{Ed}}\right); \frac{h}{30}; 0.02 \; m \right) = Max\left(abs\left(\frac{13.311}{89.617}\right); \frac{1.400}{30}; 0.02 \right) = Max(0.149; 0.047; 0.02)$$

  $e = 0.149 \; m$

- Effective height of cross-section χ :

  $\chi = h - 2 \cdot e = 1.400 - 2 \cdot 0.149 = 1.102 \; m$

- Design normal strength N_{Rd} :

  $$\eta = 1.0 - \frac{Max(f_{ck}; 50) - 50}{200} = 1.0 - \frac{Max(20; 50) - 50}{200} = 1.0 - \frac{50 - 50}{200} = 1.0$$

  $$N_{Rd} = (b \cdot \chi \cdot \eta \cdot f_{cd}) \cdot 1000 = (1.0 \cdot 1.102 \cdot 1.0 \cdot 10.667) \cdot 1000 = 11754.667 \; kN/m$$

  Result from the GEO5 – Gravity Wall program: $N_{Rd} = 11758.60 \; kNm/m$

- Usage:

  $$V_u = \frac{N_{Ed}}{N_{Rd}} \cdot 100 = \frac{89.617}{11754.667} \cdot 100 = 0.8\,\%$$, SATISFACTORY

  Result from the GEO5 – Gravity Wall program: $V_u = 0.8\,\%$ **, SATISFACTORY**

2. The Second Stage – Seismic Design Situation

Verification of the Whole Wall

The second stage of calculation uses the same wall influenced by an earthquake. The calculation of earthquake effects is made according to the Mononobe-Okabe theory. The factor of horizontal acceleration is $k_h = 0.05$ (inertial force acts horizontally in an unfavourable direction) and the factor of vertical acceleration is $k_v = -0.04$ (inertial force acts downwards). The coefficients of reduction of soil parameters and the coefficients of overall stability of construction are equal to one. Therefore, the design values of soil properties are the same as the characteristic values in Table 1.

Calculation of the weight force of the wall. To determine the horizontal and vertical components of a force from an earthquake, it is necessary to calculate the weight force of wall without the buoyancy exerted on the wall by the groundwater. The calculation is shown in Table 4.

Block	Height h_i [m]	Width b_i [m]	Area A_i [m²]	Block weight γ_i [kN/m³]	Weight force W_i [kN/m]	Point of action x_i [m]	Point of action z_i [m]	$G_i \cdot xi$	$G_i \cdot zi$
1	3.500	0.700	2.450	23	56.350	1.950	-2.550	109.883	-143.693
2	3.500	0.700	1.225	23	28.175	1.367	-1.967	38.506	-55.411
3	0.200	2.300	0.460	23	10.580	1.150	-0.700	12.167	-7.406
4	0.600	2.300	1.380	23	31.740	1.150	-0.300	36.501	-9.522
5	0.230	2.300	0.265	23	6.095	1.533	0.077	9.344	0.469
Total					132.940	-	-	206.407	-215.563

Table 4 Dimensions, weight force and centroids of the individual blocks

- Centroid of the structure:

$$x_t = \frac{\sum_1^5 Wi \cdot xi}{\sum_1^5 Wi} = \frac{206.407}{132.940} = 1.553\ m$$

$$z_t = \frac{\sum_1^5 Wi \cdot zi}{\sum_1^5 Wi} = \frac{-215.563}{132.940} = -1.622\ m$$

- Horizontal and vertical component of the force from the earthquake:

$$W_{eq,x} = k_h \cdot W = 0.05 \cdot 132.940 = 6.647\ kN/m$$

$$W_{eq,z} = -k_v \cdot W = -(-0.04) \cdot 132.940 = -5.318\ kN/m$$

Calculation of the front face resistance. The pressure at rest on the front face of the wall is the same as in the first stage of the calculation. The resultant force of the pressure at rest is $S_r = 0.430\ kN/m$.

Calculation of the active earth pressure. The course of the geostatic pressure is the same as in the first stage of calculation. In the calculation coefficients of active earth pressure K_a and K_{ac} are used as characteristic values of soil properties. The active earth pressure σ_a and the resultant force of active earth pressure S_a are calculated.

- Course of geostatic stress:
  $\sigma_{z1} = 27.000\ kPa$

  $\sigma_{z2} = 77.180\ kPa$

- Coefficients of active earth pressure in both sections:
  ($\alpha = 0°$ - back face inclination of the structure, $\beta \neq 0°$-inclination of terrain; characteristic values of soils from Table 1 are used in calculation)

  Calculation for the first layer:

$$\beta_1 = \beta = arctg\left(\frac{1}{10}\right) = 5.711°$$

$$K_{a1} = \frac{\cos^2(26.5-0)}{\cos^2(0)\cdot\cos(0+15.0)\cdot\left(1+\sqrt{\frac{\sin(26.5+15.0)\cdot\sin(26.5-5.711)}{\cos(0+15.0)\cdot\cos(0-5.711)}}\right)^2} = 0.3711$$

$$K_{ac1} = \frac{\cos(26.5)\cdot\cos(5.711)\cdot\cos(15.0-0)\cdot[1+tg(-0)\cdot tg(5.711)]}{1+\sin(26.5+15.0-0-5.711)}\cdot\frac{1}{\cos(15.0+0)} = 0.5619$$

  Calculation for the second layer:

$$\beta_2 = arctg\left(\frac{\gamma\cdot tg(\beta)}{\gamma_i}\right) = arctg\left(\frac{18.0\cdot tg(5.711)}{18.5}\right) = 5.557°$$

$$K_{a2} = \frac{\cos^2(27.0-0)}{\cos^2(0)\cdot\cos(0+15.0)\cdot\left(1+\sqrt{\frac{\sin(27.0+15.0)\cdot\sin(27.0-5.557)}{\cos(0+15.0)\cdot\cos(0-5.557)}}\right)^2} = 0.3631$$

$$K_{ac2} = \frac{\cos(27.0)\cdot\cos(5.557)\cdot\cos(15.0-0)\cdot[1+tg(-0)\cdot tg(5.557)]}{1+\sin(27.0+15.0-0-5.557)}\cdot\frac{1}{\cos(15.0+0)} = 0.5563$$

- Calculation of height in the first layer of soil MS, where the active earth pressure is neutral:

$$h_0 = \frac{2 \cdot c_{ef,1} \cdot K_{ac1}}{\gamma_1 \cdot K_{a1}} = \frac{2 \cdot 12 \cdot 0.5619}{18.0 \cdot 0.3711} = 2.019\ m \qquad > 1.50\ m$$

- Active earth pressure σ_a is calculated only for the second section (in the first section it's equal to zero):

$$\sigma_{a2a} = \sigma_{z1} \cdot K_{a2} - 2 \cdot c_{ef,d2} \cdot K_{ac2} = 27.00 \cdot 0.3631 - 2 \cdot 8.0 \cdot 0.5563 = 0.903 kPa$$

$$\sigma_{a2b} = \sigma_{z2} \cdot K_{a2} - 2 \cdot c_{ef,d2} \cdot K_{ac2} = 77.18 \cdot 0.3631 - 2 \cdot 8.0 \cdot 0.5563 = 19.123\ kPa$$

- Resultant force of the active earth pressure S_a and its horizontal and vertical components:

$$S_a = \frac{1}{2} \cdot (\sigma_{a2b} - \sigma_{a2a}) \cdot h_2 + \sigma_{a2a} \cdot h_2 = \frac{1}{2} \cdot (19.123 - 0.903) \cdot 3.03 + 0.903 \cdot 3.03 = 30.339\ kN/m$$

$$S_{ax} = S_a \cdot \cos(\delta) = 30.339 \cdot \cos(15.0) = 29.306\ kN/m$$

$$S_{az} = S_a \cdot \sin(\delta) = 30.339 \cdot \sin(15.0) = 7.852\ kN/m$$

- Point of action of the resultant force:

$$x = 2{,}300\ m$$

$$z = \frac{0.903 \cdot 3.03 \cdot \left(-\frac{3.03}{2} + 0.23\right) + (19.123 - 0.903)\frac{3.03}{2} \cdot \left(-\frac{3.03}{3} + 0.23\right)}{0.903 \cdot 3.03 + (19.123 - 0.903) \cdot \frac{3.03}{2}} = -0.826m$$

Increase of the active earth pressure caused by an earthquake. An earthquake increases the effect of active earth pressure.

- Calculation of the seismic inertia angle in the first layer (without restricted water influence):

$$\psi_1 = arctg\left(\frac{k_h}{1 - k_v}\right) = arctg\left(\frac{0.05}{1 - (-0.04)}\right) = 2.752°$$

- Calculation of the seismic inertia angle in the second layer (with restricted water influence):

$$\psi_2 = arctg\left(\frac{\gamma_{sat,2} \cdot k_h}{\gamma_{su,2} \cdot (1 - k_v)}\right) = \left(\frac{\gamma_{sat,2} \cdot k_h}{(\gamma_{sat,2} - \gamma_w) \cdot (1 - k_v)}\right) = arctg\left(\frac{20.5 \cdot 0.05}{(20.5 - 10) \cdot [1 - (-0.04)]}\right) = 5.362°$$

- Coefficient K_{ae} for the active earth pressure in both sections:

$$K_{ae} = \frac{\cos^2(\varphi - \psi - \alpha)}{\cos\psi \cdot \cos^2(\alpha) \cdot \cos(\psi + \alpha + \delta) \cdot \left(1 + \sqrt{\frac{\sin(\varphi + \delta) \cdot \sin(\varphi - \psi - \beta)}{\cos(\alpha + \delta + \psi) \cdot \cos(\alpha - \beta)}}\right)^2}$$

$$K_{ae1} = \frac{\cos^2(26.5 - 2.752 - 0)}{\cos(2.752) \cdot \cos^2(0) \cdot \cos(2.752 + 0 + 15.0) \cdot \left(1 + \sqrt{\frac{\sin(26.5 + 15.0) \cdot \sin(26.5 - 2.752 - 5.711)}{\cos(0 + 15.0 + 2.752) \cdot \cos(0 - 5.711)}}\right)^2}$$

$$K_{ae1} = 0.4102$$

$$K_{ae2} = \frac{\cos^2(27.0 - 5.362 - 0)}{\cos(5.362) \cdot \cos^2(0) \cdot \cos(2.752 + 0 + 15.0) \cdot \left(1 + \sqrt{\frac{\sin(27.0 + 15.0) \cdot \sin(27.0 - 5.362 - 5.557)}{\cos(0 + 15.0 + 5.362) \cdot \cos(0 - 5.557)}}\right)^2}$$

$$K_{ae2} = 0.4429$$

- Calculation of normal stress σ_d from the earthquake effects. The normal stress is calculated from the bottom of the wall:

$\sigma_{d2} = 0.000\ kPa$ - normal stress in the footing bottom

$$\sigma_{d1} = \gamma_2 \cdot h_2 \cdot (1 - k_v) = 16.561 \cdot 3.03 \cdot [1 - (-0.04)] = 52.187\ kPa$$

$$\sigma_{d0} = \sigma_{d1} + \gamma_1 \cdot h_1 \cdot (1 - k_v) = 52.187 + 18.0 \cdot 1.50 \cdot [1 - (-0.04)] = 80.267\ kPa$$

- Increase of the active earth pressure caused by the earthquake in both sections:

$$\sigma_{ae,1a} = \sigma_{d0} \cdot (K_{ae1} - K_{a1}) = 80.267 \cdot (0.4102 - 0.3711) = 3.138\ kPa$$

$$\sigma_{ae,1b} = \sigma_{d1} \cdot (K_{ae1} - K_{a1}) = 52.187 \cdot (0.4102 - 0.3711) = 2.041\ kPa$$

$$\sigma_{ae,2a} = \sigma_{d1} \cdot (K_{ae2} - K_{a2}) = 52.187 \cdot (0.4429 - 0.3631) = 4.165\ kPa$$

- Resultant forces of the increase of the active earth pressure S_{ae} in both sections:

$$S_{ae1} = \frac{1}{2} \cdot (\sigma_{ae,1a} - \sigma_{ae,1b}) \cdot h_1 + \sigma_{ae,1b} \cdot h_1 = \frac{1}{2} \cdot (3.138 - 2.041) \cdot 1.50 + 2.041 \cdot 1.50 = 3.884\ kN/m$$

$$S_{ae1x} = S_{ae1} \cdot \cos(\delta) = 3.884 \cdot \cos(15.0) = 3.752\ kN/m$$

$$S_{ae1z} = S_{ae1} \cdot \sin(\delta) = 3.884 \cdot \sin(15.0) = 1.005\ kN/m$$

$$S_{ae2} = \frac{1}{2} \cdot \sigma_{ae,2a} \cdot h_2 = \frac{1}{2} \cdot 4.165 \cdot 3.03 = 6.310\ kN/m$$

$$S_{ae2x} = S_{ae2} \cdot \cos(\delta) = 6.310 \cdot \cos(15.0) = 6.095\ kN/m$$

$$S_{ae2z} = S_{ae2} \cdot \sin(\delta) = 6.310 \cdot \sin(15.0) = 1.633\ kN/m$$

- Points of action of the resultant forces:
  $x_1 = 2.300\ m$

$$z_1 = \frac{2.041 \cdot 1.50 \cdot \left(-\frac{1.50}{2} - (3.03 - 0.23)\right) + (3.138 - 2.041)\frac{1.50}{2} \cdot \left(\frac{2}{3} \cdot (-1.50) - (3.03 - 0.23)\right)}{2.041 \cdot 1.50 + (3.138 - 2.041) \cdot \frac{1.50}{2}}$$

$$z_1 = -3.603\ m$$

$$x_2 = 2.300\ m$$

$$z_2 = \frac{2}{3} \cdot (-3.03) - 0.23 = -1.790\ m$$

- Total resultant force of the increase of active earth pressure S_{ae} and its horizontal and vertical component:
  $$S_{ae,x} = S_{ae1x} + S_{ae2x} = 3.752 + 6.095 = 9.847\ kN/m$$

$$S_{ae,z} = S_{ae1z} + S_{ae2z} = 1.005 + 1.633 = 2.638\ kN/m$$

$$S_{ae} = \sqrt{S_{ae,x}^{\ 2} + S_{ae,z}^{\ 2}} = \sqrt{9.847^2 + 2.638^2} = 10.194\ kN/m$$

- Point of action of the resultant force S_{ae}:
  $x_{ae} = 2.300\ m$

$$z_{ae} = \frac{3.752 \cdot (-3.603) + 6.095 \cdot (-1.790)}{3.752 + 6.095} = -2.481\ m$$

Calculation of water pressure. The water pressure is the same as in the verification of the whole wall in the first stage. The resultant force of the water pressure is $S_w = 33.330\ kN/m$ and has the same point of action as in the first stage.

Calculation of the hydrodynamic pressure acting on the front face of the wall. The action of the hydrodynamic pressure caused by the earthquake is calculated from the groundwater table to the bottom of the wall. The direction of the force is the same as the direction of the horizontal acceleration.

- Calculation of the resultant force of the hydrodynamic pressure P_{wd} caused by the earthquake:

  $H = 0.6 + 0.23 = 0.83\,m$

  $$P_{wd} = \frac{7}{12} \cdot k_h \cdot \gamma_w \cdot H^2 = \frac{7}{12} \cdot 0.05 \cdot 10.0 \cdot 0.83^2 = 0.201\,kN/m$$

- Point of action of the resultant force P_{wd}:

  $x = 2.300\,m$

  $$z = y_{wd} - 0.23 = (0.4 \cdot H) - 0.23 = (0.4 \cdot 0.83) - 0.23 = 0.102\,m$$

Checking for overturning stability. The moments calculated in the analysis rotate about the origin of the coordinate system (left bottom corner of the structure). Resisting moment M_{res} and overturning moment M_{ovr} are calculated for verification.

- Calculation of the resisting moment M_{res}:

  $$M_{res} = W \cdot r_1 + W_{eq,z} \cdot r_2 + S_{az} \cdot r_3 + S_{ae,z} \cdot r_4 = 116.484 \cdot 1.601 + 5.318 \cdot 1.553 + 7.852 \cdot 2.300 + 2.638 \cdot 2.300$$

  $$M_{res} = 116.484 \cdot 1.601 + 5.318 \cdot 1.553 + 7.852 \cdot 2.300 + 2.638 \cdot 2.300$$

  $$M_{res} = 218.877\,kNm/m$$

  Result from the GEO5 – Gravity Wall program: $M_{res} = 218.86\,kNm/m$

- Calculation of the overturning moment M_{ovr}:

  $$M_{ovr} = -S_r \cdot r_1 + W_{eq,z} \cdot r_2 + S_{ax} \cdot r_3 + S_{ae,x} \cdot r_4 + S_w \cdot r_5 + P_{wd} \cdot r_6$$

  $$M_{ovr} = -0.43 \cdot 0.200 + 6.647 \cdot 1.622 + 29.306 \cdot 0.826 + 9.847 \cdot 2.481 + 33.330 \cdot 1.056 + 0.201 \cdot 0.102$$

  $$M_{ovr} = 94.550\,kNm/m$$

  Result from the GEO5 – Gravity Wall program: $M_{ovr} = 94.59\,kNm/m$

- Usage:

$$V_u = \frac{M_{ovr}}{M_{res}} \cdot 100 = \frac{94.550}{218.877} \cdot 100 = 43.2\ \%$$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 43.2\ \%$ **, SATISFACTORY**

Checking for slip. The slip in the inclined footing bottom in 1:10 inclination is checked (Figure 4.).

- Total vertical and horizontal forces F_{ver} a F_{hor}:

$$F_{ver} = 116.484 + 5.318 + 7.852 + 2.638 = 132.292\ kN/m$$

$$F_{hor} = -0.43 + 6.647 + 29.606 + 9.847 + 33.33 = 79.000\ kN/m$$

- Normal force in the footing bottom N:

$$\alpha_b = 5.711\,°$$

$$N = F_{ver} \cdot \cos(\alpha_b) + F_{hor} \cdot \sin(\alpha_b) = 132.292 \cdot coc(5.711) + 79.000 \cdot \sin(5.711) = 139.496\ kN/m$$

- Shear force in the footing bottom T:

$$T = -F_{ver} \cdot \sin(\alpha_b) + F_{hor} \cdot \cos(\alpha_b) = -132.292 \cdot \sin(5.711) + 79.000 \cdot \cos(5.711) = 65.444\ kN/m$$

- Eccentricity of the normal force:

d - inclined width of the footing bottom

e_{alw} - maximal allowable eccentricity

$$d = \frac{2.3}{\cos(\alpha_b)} = \frac{2.3}{\cos(5.711)} = 2.311\ m$$

$$e = \frac{M_{ovr} - M_{res} + \frac{N \cdot d}{2}}{N} = \frac{94.550 - 218.877 + \frac{139.496 \cdot 2.311}{2}}{139.496} = 0.264\ m$$

In the program, the eccentricity is calculated as a ratio.

$$e_{ratio} = \frac{e}{d} = \frac{0.264}{2.311} = 0.114$$

$e_{alw} = 0{,}333 \quad \geq \quad e_{ratio} = 0.114$, SATISFACTORY

- Resisting horizontal force H_{res} and its reduction by coefficient $\gamma_S = 1.1$:

μ - reduction coefficient of contact base - soil

$\mu = 1.0$ (without reduction)

F_{res} - resisting force

$F_{res} = 0\ kN$

$$H_{res} = \left(N \cdot tg\varphi_{ef,2} + \frac{c_{ef,2} \cdot (d - 2 \cdot e)}{\mu} \right) + F_{res} = \left(139.496 \cdot tg(27.0) + \frac{8.00 \cdot (2.311 - 2 \cdot 0.264)}{1.0} \right) + 0$$

$H_{res} = 85.341\ kN/m$

Result from the GEO5 – Gravity Wall program: $H_{res} = 85.33\ kNm/m$

- Acting horizontal force H_{act}:

$H_{act} = T = 65.444\ kN/m$

Result from the GEO5 – Gravity Wall program: $H_{act} = 65.37\ kNm/m$

- Usage:

$V_u = \frac{H_{act}}{H_{res}} \cdot 100 = \frac{65.444}{85.341} \cdot 100 = 76.7\ \%$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 76.6\ \%$ **, SATISFACTORY**

Bearing Capacity of the Foundation Soil

The bearing capacity of the foundation soil is set to $R_d = 100\ kPa$, and is compared with the stress in the inclined footing bottom.

- Usage – eccentricity:

$V_u = \frac{e}{e_{alw}} \cdot 100 = \frac{0.114}{0.333} \cdot 100 = 34.2\ \%$, VYHOVUJE

Result from the GEO5 – Gravity Wall program: $V_u = 34.6\ \%$ **, SATISFACTORY**

- Stress in the footing bottom σ:

$\sigma = \frac{N}{d - 2 \cdot e} = \frac{139.496}{2.311 - 2 \cdot 0.264} = 78.237\ kPa$

Result from the GEO5 – Gravity Wall program: $\sigma = 78.29\ kPa$

- Usage:

$$V_u = \frac{\sigma}{R_d} \cdot 100 = \frac{78.237}{100} \cdot 100 = 78.2\,\%$$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 78.3\,\%$ **, SATISFACTORY**

Dimensioning – Wall Stem Check

In this example, the cross-section on the level of the x-axis in Figure 5 is verified. The cross-section is made from plain concrete C 20/25 (characteristic cylindrical strength of concrete in compression $f_{ck} = 20000\ kPa$, characteristic strength of concrete in tension $f_{ctm} = 2200\ kPa$) with height $h = 1.40\ m$ and width $b = 1.00\ m$. The verification of the cross-section made from plain concrete is realized in accordance with EN 1992-1-1.

- Calculation of the weight force and the centroid is the same as in the first stage:

$$W = 84.525\ kN/m$$

$$x_t = 0.856\ m$$

$$z_t = -1.556\ m$$

- Horizontal and vertical component of the force caused by the earthquake (the centroid is the same as the centroid of the weight force):

$$W_{eq,x} = k_h \cdot W = 0.05 \cdot 84.525 = 4.226\ kN/m$$

$$W_{eq,z} = -k_v \cdot W = -(-0.04) \cdot 84.525 = -3.381\ kN/m$$

Calculation of the active earth pressure. The area behind the evaluated part of the construction is divided into two sections. The centroids of all forces must be recalculated.

- Vertical geostatic stress σ_{z1} and σ_{z2} in both sections:

$$\sigma_{z1} = \gamma_1 \cdot h_2 = 18.0 \cdot 1.5 = 27.000\ kPa$$

$$\sigma_{z2} = \sigma_{z1} + \gamma_2 \cdot h_2 = 27.0 + 16.561 \cdot 2.0 = 60.122\ kPa$$

- Active earth pressure in the second section σ_{a2a} and σ_{a2b} (the active earth pressure in the first section is equal to zero):

$$\sigma_{a2a} = 0.3631 \cdot 27.000 - 2 \cdot 8.0 \cdot 0.5563 = 0.903\ kPa$$

$$\sigma_{a2b} = 0.3631 \cdot 60.122 - 2 \cdot 8.0 \cdot 0.5563 = 12.929\ kPa$$

- Total resultant force of the active earth pressure S_a and its horizontal and vertical components:

$$S_a = \frac{1}{2} \cdot (12.929 - 0.903) \cdot 2.0 + 0.903 \cdot 2.0 = 13.832\ kN/m$$

$$S_{a,x} = S_{a2} \cdot \cos(\delta) = 13.832 \cdot \cos(15.0) = 13.360\ kN/m$$

$$S_{a,z} = S_{a2} \cdot \sin(\delta) = 13.832 \cdot \sin(15.0) = 3.580\ kN/m$$

- Point of action of the resultant force S_a

$x = 1.400 m$

$$z = \frac{0.903 \cdot 2.00 \cdot \left(-\frac{2.00}{2}\right) + (12.929 - 0.903) \cdot \frac{2.00}{2} \cdot \left(-\frac{2.00}{3}\right)}{0.903 \cdot 2.00 + (12.929 - 0.903) \cdot \frac{2.00}{2}} = -0.710\ m$$

Increase of the active earth pressure caused by an earthquake. An earthquake increases the effect of the active earth pressure.

- Calculation of the normal stress σ_d from the earthquake effects. The vertical pressure is calculated from the lower part of the stem:

$\sigma_{d2} = 0.000\ kPa$ - normal stress at the level of the lower part of the stem

$$\sigma_{d1} = \gamma_2 \cdot (h_2) \cdot (1 - k_v) = 16.561 \cdot (2.00) \cdot [1 - (-0.04)] = 34.447\ kPa$$

$$\sigma_{d0} = \sigma_{d1} + \gamma_1 \cdot h_1 \cdot (1 - k_v) = 34.447 + 18.0 \cdot 1.50 \cdot [1 - (-0.04)] = 62.527\ kPa$$

- Increase of the active earth pressure caused by the earthquake effects in both sections:

$$\sigma_{ae,1a} = \sigma_{d0} \cdot (K_{ae1} - K_{a1}) = 62.527 \cdot (0.4102 - 0.3711) = 2.445\ kPa$$

$$\sigma_{ae,1b} = \sigma_{d1} \cdot (K_{ae1} - K_{a1}) = 34.447 \cdot (0.4102 - 0.3711) = 1.347 kPa$$

$$\sigma_{ae,2a} = \sigma_{d1} \cdot (K_{ae2} - K_{a2}) = 34.447 \cdot (0.4429 - 0.3631) = 2.749\ kPa$$

- Resultant forces of the increase of the active earth pressure S_{ae} in both sections:

$$S_{ae1} = \frac{1}{2} \cdot (\sigma_{ae,1a} - \sigma_{ae,1b}) \cdot h_1 + \sigma_{ae,1b} \cdot h_1 = \frac{1}{2} \cdot (2.445 - 1.347) \cdot 1.50 + 1.347 \cdot 1.50 = 2.844\ kN/m$$

$$S_{ae1x} = S_{ae1} \cdot \cos(\delta) = 2.844 \cdot \cos(15.0) = 2.747\ kN/m$$

$$S_{ae1z} = S_{ae1} \cdot \sin(\delta) = 2.844 \cdot \sin(15.0) = 0.736\ kN/m$$

$$S_{ae2} = \frac{1}{2} \cdot \sigma_{ae,2a} \cdot h_2 = \frac{1}{2} \cdot 2.749 \cdot 2.00 = 2.749\ kN/m$$

$$S_{ae2x} = S_{ae2} \cdot \cos(\delta) = 2.749 \cdot \cos(15.0) = 2.655 kN/m$$

$$S_{ae2z} = S_{ae2} \cdot \sin(\delta) = 2.749 \cdot \sin(15.0) = 0.711\ kN/m$$

- Points of action of the resultant forces:

$x_1 = 1.400\ m$

$$z_1 = \frac{1.347 \cdot 1.50 \cdot \left(-\frac{1.50}{2} - 200\right) + (2.445 - 1.347)\frac{1.50}{2} \cdot \left(\frac{2}{3} \cdot (-1.50) - 2.00\right)}{1.347 \cdot 1.50 + (2.445 - 1.347) \cdot \frac{1.50}{2}} = -2.824\ m$$

$x_2 = 1.400\ m$

$$z_2 = \frac{2}{3} \cdot (-2.0) = -1.333\ m$$

- Total resultant force S_{ae} and its horizontal and vertical components:

$$S_{ae,x} = S_{ae1x} + S_{ae2x} = 2.747 + 2.655 = 5.402\ kN/m$$

$$S_{ae,z} = S_{ae1z} + S_{ae2z} = 0.736 + 0.711 = 1.447\ kN/m$$

$$S_{ae} = \sqrt{S_{ae,x}{}^2 + S_{ae,z}{}^2} = \sqrt{5.402^2 + 1.447^2} = 5.592\ kN/m$$

- Point of action of the resultant force S_{ae}:

$x_{ae} = 1.400\ m$

$$z_{ae} = \frac{2.747 \cdot (-2.824) + 2.655 \cdot (-1.333)}{2.747 + 2.655} = -2.091\ m$$

Calculation of the water pressure. Water pressure becomes higher with the increasing depth.

- Horizontal water pressure σ_w in depth of 3.5 m under the surface of the adjusted terrain:
- $\sigma_w = \gamma_w \cdot (3.5 - 1.5) = 10 \cdot 2.0 = 20.000\ kPa$

- Resultant force of the water pressure S_w:

$$S_w = \frac{1}{2} \cdot \sigma_w \cdot h_w = \frac{1}{2} \cdot 20.000 \cdot 2.0 = 20.000\ kN/m$$

- Point of action of the resultant force S_w:

$x_1 = 1.400\ m$

$$z_1 = -\frac{1}{3} \cdot 2,0 = -0.667\ m$$

Verification of shear strength. The design shear force, design normal force, design bending moment and shear strength of the cross-section are calculated. The design bending moment rotates about the middle of the verified cross-section.

- Design shear force V_{Ed}:

$$V_{Ed} = S_w + S_{a,x} + S_{ae,x} + W_{eq,x} = 20.000 + 13.360 + 5.402 + 4.226 = 42.988\ kN/m$$

Result from the GEO5 – Gravity Wall program: $V_{Ed} = 42.95\ kN/m$

- Design normal force N_{Ed}:

$$N_{Ed} = S_{a,z} + S_{ae,z} + W + W_{eq,z} = 3.580 + 1.447 + 84.525 + 3.381 = 92.933\ kN/m$$

Result from the GEO5 – Gravity Wall program: $N_{Ed} = 92.89\ kN/m$

- Design bending moment M_{Ed}:

$$M_{Ed} = -W \cdot r_1 - S_{az} \cdot r_2 + S_{ax} \cdot r_3 + S_w \cdot r_4 - W_{eq,z} \cdot r_5 - S_{ae,z} \cdot r_6 + W_{eq,x} \cdot r_7 + S_{ae,x} \cdot r_8$$

$$M_{Ed} = -84.525 \cdot (0.856 - 0.700) - 3.580 \cdot 0.700 + 13.360 \cdot 0.710 + 2.,0 \cdot 0.667 - \\ - 3.381 \cdot (0.856 - 0.700) - 1.447 \cdot 0.700 + 4.226 \cdot 1.556 + 5.402 \cdot 2.091$$

$$M_{Ed} = 23.458\ kNm/m$$

Result from the GEO5 – Gravity Wall program: $M_{Ed} = 23.46\ kNm/m$

- Calculation of the area of compressed concrete A_{cc}:

Determining the compressed area of concrete is necessary in order to determine the stresses on the front and the rear edges of the verified cross-section. The normal force N_{Ed} makes compressive stress and therefore is considered to be a negative force.

Stress from design normal force N_{Ed}:

$$\frac{N}{A} = \frac{N_{Ed}}{A} = \frac{-92.933}{1.00 \cdot 1.40} = -66.381\ kPa$$

Stress from design bending moment M_{Ed} :

$$\pm\frac{M}{W}=\pm\frac{M_{Ed}}{W_y}=\frac{23.458}{\frac{1}{6}\cdot 1.00\cdot 1.40^2}=\pm 71.810\ kPa$$

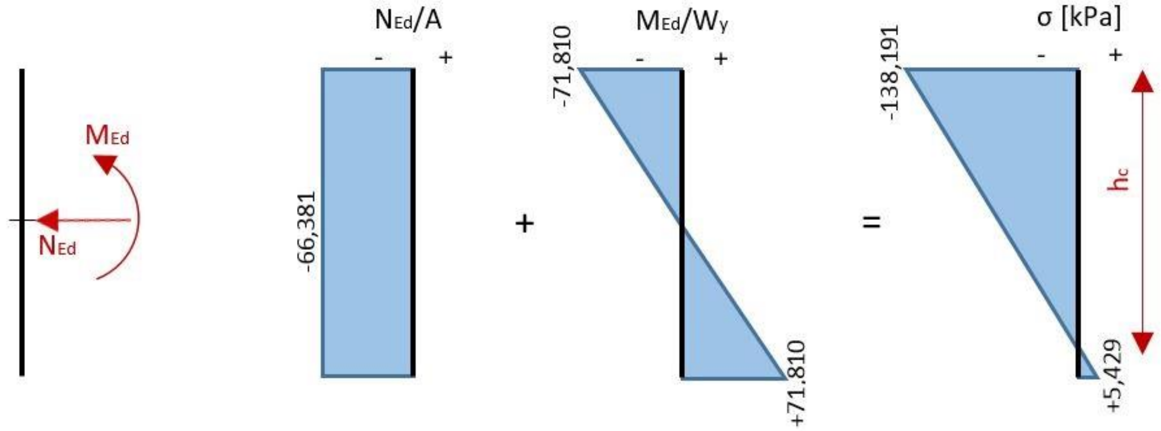

Figure 7 Course of tension on the cross-section of wall stem

From Figure 7 it can be seen, that not the whole cross section is compressed, only a part, h_c :

$$h_c=\frac{138.191}{\frac{138.191+5.429}{1.400}}=1.347\ m$$

$$A_{cc}=b\,.\,h_c=1.00\cdot 1.347=1.347\ m^2$$

- Stress on the cross-section area σ_{cp} :

$$\sigma_{cp}=\frac{N_{Ed}}{A_{cc}}\cdot\frac{1}{1000}=\frac{92.933}{1.347}\cdot\frac{1}{1000}=0.06899\ MPa$$

- Design strength of concrete in compression f_{cd} :

$$f_{cd}=\alpha_{cc,pl}\cdot\frac{f_{ck}}{\gamma_c}=0.8\cdot\frac{20.00}{1,5}=10.667\ MPa$$

- Design strength of concrete in tension f_{ctd} :

  $f_{ctk,005}$ - lower value of characteristic strength of concrete in tension

$$f_{ctd}=\alpha_{ct,pl}\cdot\frac{f_{ctk,005}}{\gamma_c}=\alpha_{ct,pl}\cdot\frac{0.7\cdot f_{ctm}}{\gamma_c}=0.8\cdot\frac{0.7\cdot 2.20}{1.5}=0.821\ MPa$$

- Limit stress:

$$\sigma_{c,\lim} = f_{cd} - 2 \cdot \sqrt{f_{ctd} \cdot (f_{cd} + f_{ctd})} = 10.667 - 2 \cdot \sqrt{0.821 \cdot (10.667 + 0.821)} = 4.525\ MPa$$

- Shear strength f_{cvd} :

$$f_{cvd} = \sqrt{f_{ctd}^2 + \sigma_{cp} \cdot f_{ctd} - \left(\frac{\max(0, \sigma_{cp} - \sigma_{c,\lim}}{2}\right)^2} = \sqrt{0.821^2 + 0.06899 \cdot 0.821 - \left(\frac{\max(0;0.066 - 4.525}{2}\right)^2}$$

$$f_{cvd} = 0.855\ MPa$$

- Design shear strength V_{Rd} :

$$k = 1.5$$

$$V_{Rd} = \frac{f_{cvd} \cdot A_{cc}}{k} \cdot 1000 = \frac{0.855 \cdot 1.347}{1.5} \cdot 1000 = 767.790\ kN/m$$

Result from the GEO5 – Gravity Wall program: $V_{Rd} = 767.58\ kN/m$

- Usage:

$V_u = \frac{V_{Ed}}{V_{Rd}} \cdot 100 = \frac{42.988}{767.790} \cdot 100 = 5.6\ \%$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 5.6\ \%$**, SATISFACTORY**

Verification of a cross-section loaded by bending moment and normal force.

- Calculation of eccentricity e :

$$e = Max\left(abs\left(\frac{M_{Ed}}{N_{Ed}}\right); \frac{h}{30}; 0.02\ m\right) = Max\left(abs\left(\frac{23.458}{92.933}\right); \frac{1.400}{30}; 0.02\right) = Max(0.252;\ 0.047;\ 0.02)$$

$$e = 0.252\ m$$

- Effective high of cross-section χ :

$$\chi = h - 2 \cdot e = 1.400 - 2 \cdot 0.252 = 0.896\ m$$

- Design normal strength N_{Rd} :

$$\eta = 1{,}0 - \frac{Max(f_{ck}; 50) - 50}{200} = 1{,}0 - \frac{Max(20; 50) - 50}{200} = 1{,}0 - \frac{50 - 50}{200} = 1.0$$

$$N_{Rd} = (b \cdot \chi \cdot \eta \cdot f_{cd}) \cdot 1000 = (1.0 \cdot 0.896 \cdot 1.0 \cdot 10.667) \cdot 1000 = 9557.632\ kN/m$$

Result from the GEO5 – Gravity Wall program: $N_{Rd} = 9543.22\ kNm/m$

- Usage:

$$V_u = \frac{N_{Ed}}{N_{Rd}} \cdot 100 = \frac{92.933}{9557.632} \cdot 100 = 1.0\,\%$$, SATISFACTORY

Result from the GEO5 – Gravity Wall program: $V_u = 1.0\,\%$ **, SATISFACTORY**