Verification Manual

of GEO5 Gravity Wall program

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Verze: **1.0-en**

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INTRODUCTION

This Gravity Wall program Verification Manual contains hand-made calculation of following problems:

- calculation of earth pressures
- calculation of hydrodynamic pressure
- verification of the wall with the help of theory of limit states
- dimensioning of wall section according to EN 1992-1-1 [1]
- verification of the wall influenced by earthquake according to Mononobe-Okabe theory [2], [3]

In general this Verification Manual has been made to show the ability of the GEO5 software to provide a solution consistent with the result of hand-made calculations or textbook solutions.

Results of hand-made calculations are compared with the results from GEO5 Gravity Wall program.

For further details please refer to our verification example file (`Demo.gtz` – download http://www.finesoftware.eu/references/verification-manuals/) using our program GEO5 Gravity Wall (http://www.finesoftware.eu/geotechnical-software/gravity-wall/).

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1 Example 1

1.1 Problem description

In Fig. 1 is shown example of gravity wall with inclined footing bottom (inclination 1:10). Earth body is compounded from two soil layers and terrain is inclined (1:10). Top layer (depth 1.5 m) is formed from sandy silt (MS), lower layer is clayey sand (SC) at front face and back face of the wall. Groundwater table is in the level of layer SC, i.e. 1.5 m behind the wall and 3.7 m in front of the wall. Soil properties (effective parameters) are mentioned in the Tab. 1. Wall is made from plain concrete (bulk weight $\gamma = 23$ kN/m^3). Verification analysis of the wall is performed with the help of theory of limit states.

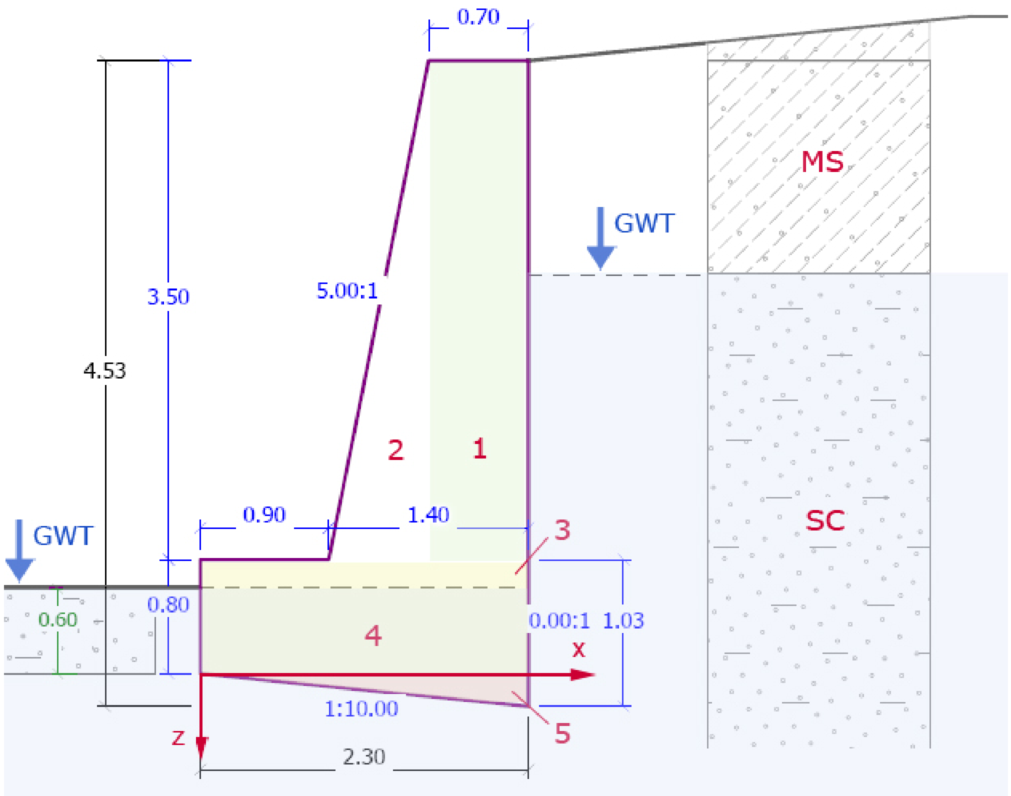

Figure 1: Wall - geometry

Soil parameters (angle of friction and cohesion) are reduced by coefficients $\gamma_{m\varphi} = 1.1$ a $\gamma_{mc} = 1.4$. Design values used in calculation are in Tab. 2.

1.2 Verification of the whole wall

Calculation of weight and centroid of the wall. Wall is divided into 5 parts (Fig. 1). Parts 4 and 5 are under groundwater table, therefore bulk weight of concrete is reduced,

		MS	SC	
bulk weight	γ	18.000	18.500	[kN/m^3]
bulk weight of satur. soil	γ_{sat}	20.000	20.500	[kN/m^3]
angle of internal friction	φ	26.500	27.000	[°]
cohesion	c	12.000	8.000	[kPa]
angle of friction struc-soil	δ	15.000	15.000	[°]
Poisson ratio	ν	0.350	0.350	-

Table 1: Soil properties - effective values

		MS	SC	
angle of internal friction	φ_d	24.091	24.545	[°]
cohesion	c_d	8.571	5.714	[kPa]
angle of friction struc-soil	δ_d	13.636	13.636	[°]

Table 2: Design parameters of soil

i.e. γ = 23 - 10 = 13 kN/m^3. In the Tab. 3 are shown dimensions of the parts of the wall, their weights and centroids.

	height	width	area	b. weight	weight force	point of action			
block	h_i[m]	w_i[m]	A_i[m^2]	γ[kN/m^3]	W_i[kN/m]	x_i[m]	z_i[m]	$W_i \cdot x_i$	$W_i \cdot z_i$
1	0.350	0.700	2.450	23	56.350	1.950	-2.550	109.883	-143.693
2	0.350	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	5.272	0.264
TOTAL					116.484			186.459	-211.628

Table 3: Weight of construction and centroids of its parts

▷ Centroid of the construction:

$$x = \frac{\sum_{i=1}^{5} W_i \cdot x_i}{W} = \frac{186.459}{116.484} = 1.601 \quad \text{m}$$

$$z = \frac{\sum_{i=1}^{5} W_i \cdot z_i}{W} = \frac{-211.628}{116.484} = -1.817 \quad \text{m}$$

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

▷ For cohesive soils the Terzaghi formula is used for computing of coefficient of earth pressure at rest Kr:

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

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

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

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

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

▷ Vertical normal effective stress σ_z in the footing bottom:

$$\sigma_z = \gamma \cdot h = 4.439 \cdot 0.6 = 2.664 \quad \mathrm{kPa}$$

▷ Pressure at rest σ_r in the footing bottom:

$$\sigma_r = K_r \cdot \sigma_z = 0.538 \cdot 2.664 = 1.434 \quad \mathrm{kPa}$$

▷ Resultant force of stress at rest S_r:

$$S_r = \frac{1}{2} \cdot \sigma_r \cdot h = \frac{1}{2} \cdot 1.434 \cdot 0.6 = 0.430 \quad \mathrm{kN/m}$$

▷ Resultant force S_r is horizontally oriented, therefore:

$$S_{rx} = S_r = 0.430 \quad \mathrm{kN/m} \qquad S_{rz} = 0 \quad \mathrm{kN/m}$$

▷ Point of action of resultant force S_r:

$$x = 0 \quad \mathrm{m}$$

$$z = -\frac{h}{3} = -\frac{0.6}{3} = -0.200 \quad \mathrm{m}$$

Calculation of active pressure. Construction is at interface between soils MS and SC divided into two levels, in each is calculated geostatic pressure σ_z, active pressure σ_a and resultant force S_a (Fig. 2).

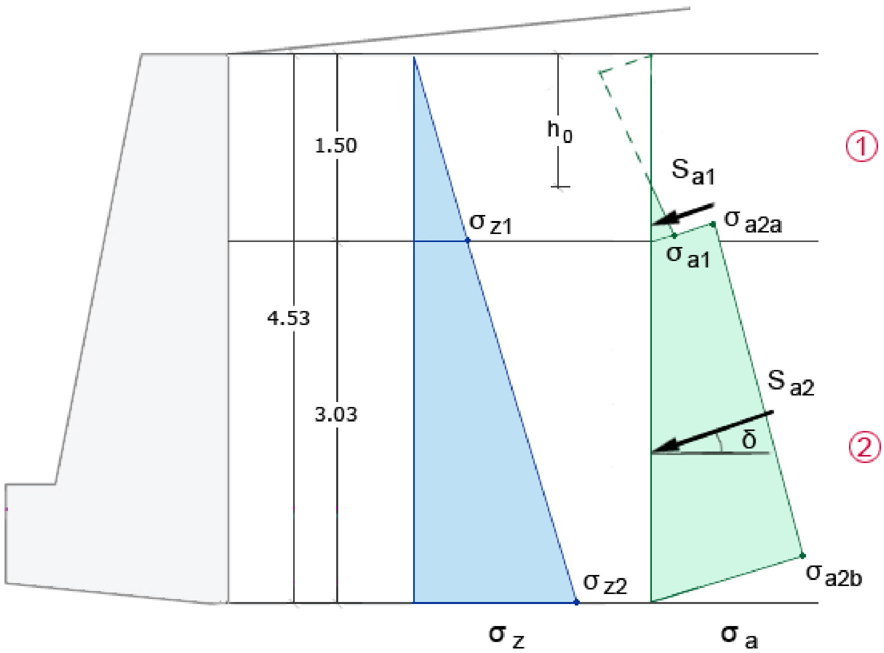

Figure 2: Geostatic pressure σ_z and active pressure σ_a

▷ Coefficients of the active pressure in both levels (back face inclination of the structure $\alpha = 0°$, inclination of terrain $\beta \neq 0°$):

$$K_a = \frac{\cos^2(\varphi_d - \alpha)}{\cos^2\alpha \cdot \cos(\alpha + \delta_d) \cdot \left[1 + \sqrt{\frac{\sin(\varphi_d+\delta_d)\cdot\sin(\varphi_d-\beta)}{\cos(\alpha+\delta_d)\cdot\cos(\alpha-\beta)}}\right]^2}$$

$$K_{ac} = \frac{\cos\varphi_d \cdot \cos\beta \cdot \cos(\delta_d - \alpha) \cdot (1 + \tan(-\alpha) \cdot \tan\beta)}{(1 + \sin(\varphi_d + \delta_d - \alpha - \beta)) \cdot (\cos\alpha + \delta_d)}$$

$$\beta_1 = \arctan\frac{1}{10} = 5.711°$$

$$K_{a1} = \frac{\cos^2 24.091}{\cos 13.636 \cdot \left[1 + \sqrt{\frac{\sin(24.091+13.636)\cdot\sin(24.091-5.711)}{\cos 13.636\cdot\cos(-5.711)}}\right]^2} = 0.410$$

$$K_{ac1} = \frac{\cos 24.091 \cdot \cos 5.711 \cdot \cos 13.636 \cdot (1 + \tan 0 \cdot \tan 5.711)}{(1 + \sin(24.091 + 13.636 - 5.711)) \cdot \cos 13.636} = 0.594$$

$$\beta_2 = \arctan \frac{\gamma_1 \cdot \tan \beta_1}{\gamma_2} = \arctan \frac{18 \cdot \tan 5.711}{18.5} = 5.557^\circ$$

$$K_{a2} = \frac{\cos^2 24.545}{\cos 13.636 \cdot \left[1 + \sqrt{\frac{\sin(24.545+13.636)\cdot\sin(24.545-5.557)}{\cos 13.636\cdot\cos(-5.557)}}\right]^2} = 0.402$$

$$K_{ac2} = \frac{\cos 24.545 \cdot \cos 5.557 \cdot \cos 13.636 \cdot (1 + \tan 0 \cdot \tan 5.557)}{(1 + \sin(24.545 + 13.636 - 5.557)) \cdot \cos 13.636} = 0.588$$

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

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

▹ Vertical geostatic stress σ_z in 2 levels:

$$\sigma_{z1} = \gamma_1 \cdot h_1 = 18 \cdot 1.5 = 27.000 \quad \text{kPa}$$

$$\sigma_{z2} = \sigma_{z1} + \gamma_2 \cdot h_2 = 27 + 16.561 \cdot 3.03 = 77.179 \quad \text{kPa}$$

▹ Active pressure σ_a in 2 levels:

$$\sigma_{a1} = K_{a1} \cdot \sigma_{z1} - 2 \cdot c_{d1} \cdot K_{ac1} = 0.410 \cdot 27.000 - 2 \cdot 8.571 \cdot 0.594 = 0.886 \quad \text{kPa}$$

$$\sigma_{a2a} = K_{a2} \cdot \sigma_{z1} - 2 \cdot c_{d2} \cdot K_{ac2} = 0.402 \cdot 27.000 - 2 \cdot 5.714 \cdot 0.588 = 4.121 \quad \text{kPa}$$

$$\sigma_{a2b} = K_{a2} \cdot \sigma_{z2} - 2 \cdot c_{d2} \cdot K_{ac2} = 0.402 \cdot 77.179 - 2 \cdot 5.714 \cdot 0.588 = 24.274 \quad \text{kPa}$$

▹ Depth h_0 in the first layer of soil MS, where is neutral active pressure ($\sigma_a = 0$ kPa):

$$h_0 = \frac{2 \cdot c_{d1} \cdot K_{ac1}}{\gamma_1 \cdot K_{a1}} = \frac{2 \cdot 8.571 \cdot 0.594}{18 \cdot 0.410} = 1.380 \quad \text{m}$$

▹ Resultant forces of the active pressure S_a and horizontal, resp. vertical components:

$$S_{a1} = 0.5 \cdot \sigma_{a1} \cdot (h_1 - h_0) = 0.5 \cdot 0.886 \cdot (1.5 - 1.38) = 0.053 \quad \text{kN/m}$$

$$S_{ax1} = S_{a1} \cdot \cos \delta_{d1} = 0.053 \cdot \cos 13.636 = 0.052 \quad \text{kN/m}$$

$$S_{az1} = S_{a1} \cdot \sin \delta_{d1} = 0.053 \cdot \sin 13.636 = 0.013 \quad \text{kN/m}$$

$$S_{a2} = 0.5 \cdot (\sigma_{a2b} - \sigma_{a2a}) \cdot h_2 + \sigma_{a2a} \cdot h_2$$

$$S_{a2} = 0.5 \cdot (24.274 - 4.121) \cdot 3.03 + 4.121 \cdot 3.03 = 43.019 \quad \text{kN/m}$$

$$S_{ax2} = S_{a2} \cdot \cos \delta_{d2} = 43.019 \cdot \cos 13.636 = 41.807 \quad \text{kN/m}$$

$$S_{az2} = S_{a2} \cdot \sin \delta_{d2} = 43.019 \cdot \sin 13.636 = 10.142 \quad \text{kN/m}$$

▹ Points of action of resultant forces S_a:

$$x_1 = 2.300 \quad \text{m}$$

$$z_1 = -0.8 - 2 - \frac{(1.5 - 1.38)}{3} = -2.840 \quad \text{m}$$

$$x_2 = 2.300 \quad \text{m}$$

$$z_2 = -\frac{\frac{1}{6} \cdot 3.03^2 \cdot (24.274 - 4.121) + \frac{1}{2} \cdot 3.03^2 \cdot 4.121}{\frac{1}{2} \cdot 3.03 \cdot (24.274 - 4.121) + 3.03 \cdot 4.121} + 0.23 = -0.927 \quad \text{m}$$

▹ Total resultant force of the active pressure S_a and horizontal, resp. vertical component:

$$S_{ax} = \sum_{i=1}^{2} S_{axi} = 0.052 + 41.807 = 41.859 \quad \text{kN/m}$$

$$S_{az} = \sum_{i=1}^{2} S_{azi} = 0.013 + 10.142 = 10.155 \quad \text{kN/m}$$

$$S_a = \sqrt{S_{ax}^2 + S_{az}^2} = \sqrt{41.859^2 + 10.155^2} = 43.073 \quad \text{kN/m}$$

▷ Point of action of the resultant force S_a:

$$x = \frac{\sum_{i=1}^{2} S_{azi} \cdot x_i}{S_{az}} = \frac{0.029 + 23.327}{10.155} = 2.300 \quad \text{m}$$

$$z = \frac{\sum_{i=1}^{2} S_{axi} \cdot z_i}{S_{ax}} = \frac{-0.147 - 38.738}{41.859} = -0.929 \quad \text{m}$$

Calculation of water pressure. The heel of a structure is sunk into permeable subsoil, which allows free water flow below the structure. Therefore acting of hydrodynamic pressure is considered and its resultant force is calculated (Fig. 3).

▷ Horizontal water pressure σ_w at interface of level 1 and 2:

$$\sigma_{w1} = \gamma_w \cdot h_1 = 10 \cdot 2.2 = 22.000 \quad \text{kPa}$$

▷ Resultant forces of water pressure S_w in 2 levels:

$$S_{w1} = \frac{1}{2} \cdot \sigma_{w1} \cdot h_1 = \frac{1}{2} \cdot 22 \cdot 2.2 = 24.200 \quad \text{kN/m}$$

$$S_{w2} = \frac{1}{2} \cdot \sigma_{w1} \cdot h_2 = \frac{1}{2} \cdot 22 \cdot 0.83 = 9.130 \quad \text{kN/m}$$

▷ Points of action of resultant forces:

$$x_1 = 2.300 \quad \text{m} \qquad z_1 = -0.6 - \frac{2.2}{3} = -1.333 \quad \text{m}$$

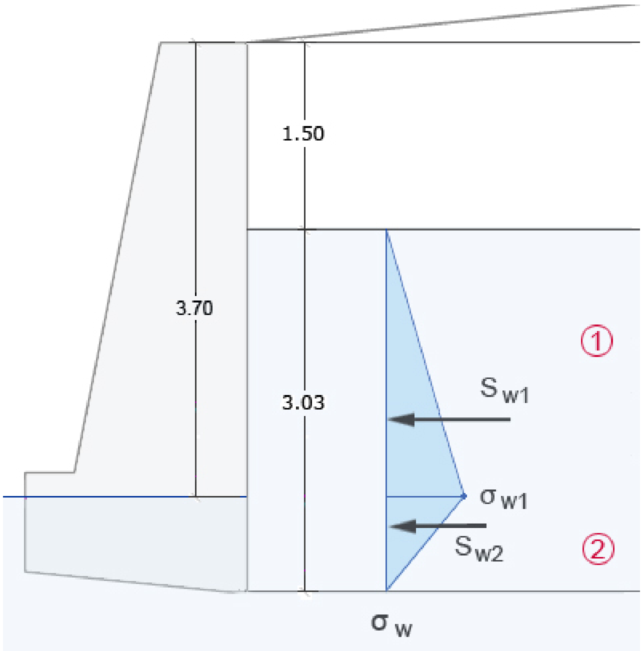

Figure 3: Hydrodynamic pressure σ_w

$$x_2 = 2.300 \quad \text{m} \qquad z_2 = -0.6 + \frac{0.83}{3} = -0.323 \quad \text{m}$$

▷ Total resultant force of the water pressure S_w:

$$S_w = \sum_{i=1}^{2} S_{wi} = 24.2 + 9.130 = 33.330 \quad \text{kN/m}$$

▷ Total point of action of the resultant force S_w:

$$x = 2.300 \quad \text{m}$$

$$z = \frac{\sum_{i=1}^{2} S_{wi} \cdot z_i}{S_w} = \frac{-32.267 - 2.952}{33.330} = -1.057 \quad \text{m}$$

Checking for overturning stability. The moment rotates around the beginning of system of coordinates (left bottom corner of the footing).

▷ Resisting moment M_r is reduced by coefficient of overall stability of structure $\gamma_s = 0.9$:

$$M_r = 0.9 \cdot (116.484 \cdot 1.601 + 10.155 \cdot 2.3) = 188.833 \quad \text{kNm/m}$$

Result from program GEO5 Gravity Wall: $M_r = 188.83 \quad \text{kNm/m}$

▷ Driving moment M_o:

$$M_o = -0.430 \cdot 0.2 + 41.859 \cdot 0.929 + 33.33 \cdot 1.057 = 74.017 \quad \text{kNm/m}$$

Result from program GEO5 Gravity Wall: $M_o = 74.02 \quad \text{kNm/m}$

▷ Usage:

$$V_u = \frac{M_o}{M_r} \cdot 100 = \frac{74.017}{188.833} \cdot 100 = 39.2 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 39.2 \quad \% \quad \text{O.K.}$

Checking for slip. Slip in the inclined footing bottom is checked. (Fig. 4).

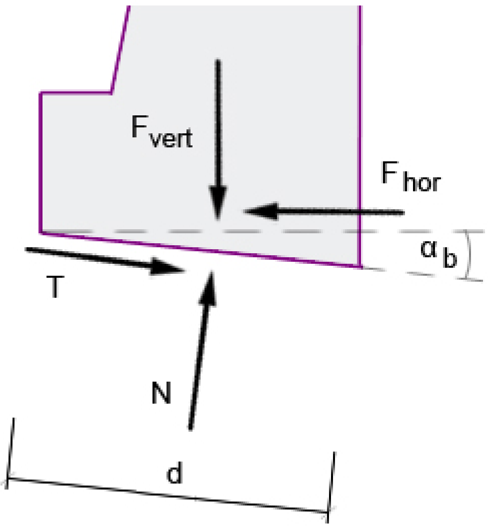

Figure 4: Forces acting in the footing bottom - normal and shear soil reaction N and T, total vertical and horizontal forces acting on the structure F_{vert} and F_{hor}

▷ Total vertical and horizontal forces F_{vert} and F_{hor}:

$$F_{vert} = 116.484 + 10.155 = 126.638 \quad \text{kN/m}$$

$$F_{hor} = -0.430 + 41.859 + 33.330 = 74.758 \quad \text{kN/m}$$

▷ Normal force in the footing bottom (inclination of footing bottom $\alpha_b = 5.711°$, see Fig. 4):

$$N = F_{vert} \cdot \cos\alpha_b + F_{hor} \cdot \sin\alpha_b$$

$$N = 126.638 \cdot \cos 5.711 + 74.758 \cdot \sin 5.711 = 133.449 \quad \text{kN/m}$$

▷ Shear reaction in the footing bottom:

$$T = -F_{vert} \cdot \sin\alpha_b + F_{hor} \cdot \cos\alpha_b$$

$$T = -126.638 \cdot \sin 5.711 + 74.758 \cdot \cos 5.711 = 61.786 \quad \text{kN/m}$$

▷ Eccentricity of the normal force (inclined width of the footing bottom $d = 2.311$ m):

$$e = \frac{d}{2} - \frac{\frac{M_r}{0.9} - M_o}{N} = \frac{2.311}{2} - \frac{\frac{188.830}{0.9} - 74.017}{133.449} = 0.138 \quad \text{m}$$

▷ Maximal allowable eccentricity:

$$e_{alw} = \frac{d}{3} = \frac{2.311}{3} = 0.770 \quad \text{m} \quad > \quad e = 0.138 \quad \text{m} \quad \text{O.K.}$$

▷ Resisting force H_r:

$$H_r = \gamma_s \cdot (N \cdot \tan\varphi_d + c_d \cdot (d - 2 \cdot e))$$

$$H_r = 0.9 \cdot (133.449 \cdot \tan 24.545 + 5.714 \cdot (2.311 - 2 \cdot 0.138)) = 65.316 \quad \text{kN/m}$$

Result from program GEO5 Gravity Wall: $H_r = 65.38 \quad \text{kN/m}$

▷ Driving force H_d:

$$H_d = T = 61.786 \quad \text{kN/m}$$

Result from program GEO5 Gravity Wall: $H_d = 61.79 \quad \text{kN/m}$

▷ Usage:

$$V_u = \frac{H_d}{H_r} \cdot 100 = \frac{61.786}{65.316} \cdot 100 = 94.6 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 94.5 \quad \% \quad \text{O.K.}$

1.3 Bearing capacity of the foundation soil

Bearing capacity of the foundation soil is set as $R_d = 100$ kPa and is compared with stress in the inclined footing bottom.

▷ Usage - eccentricity:

$$V_u = \frac{e}{e_{alw}} \cdot 100 = \frac{0.138}{0.770} \cdot 100 = 17.9 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 17.4 \quad \% \quad \text{O.K.}$

▷ Stress in the footing bottom:

$$\sigma = \frac{N}{(d - 2 \cdot e)} = \frac{133.449}{(2.311 - 2 \cdot 0.138)} = 65.570 \quad \text{kPa}$$

Result from program GEO5 Gravity Wall: $\sigma = 65.20 \quad \text{kPa}$

▷ Usage:

$$V_u = \frac{\sigma}{R_d} \cdot 100 = \frac{65.570}{100} \cdot 100 = 65.57 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 65.2 \quad \% \quad \text{O.K.}$

1.4 Dimensioning - analysis of wall section

Cross-section in the level of the x-axis in Fig. 5 is analysed. Rectangular section (width $b = 1$ m, height $h = 1.4$ m) is made from plain concrete C20/25 (characteristic strength of concrete in tension $f_{ctk} = 2200$ kPa, characteristic cylindrical strength of concrete in compression $f_{ck} = 20000$ kPa). Verification of cross-section made from plain concrete is realized according to EN 1992 1-1 [1].

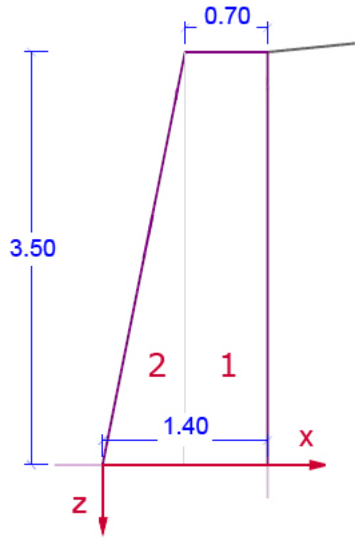

Figure 5: Dimensioning of cross-section

Calculation of weight and centroid of the wall. ▷ Weight of the construction:

$$W = 23 \cdot (3.5 \cdot 0.7 + 0.5 \cdot 3.5 \cdot 0.7) = 84.525 \quad \text{m}$$

▷ Centroid of the construction:

$$x = \frac{23 \cdot (3.5 \cdot 0.7 \cdot (0.7 + 0.35) + 0.5 \cdot 3.5 \cdot 0.7 \cdot \frac{2 \cdot 0.7}{3})}{84.525} = 0.856 \quad \text{m}$$

$$z = \frac{23 \cdot (3.5 \cdot 0.7 \cdot -\frac{3.5}{2} + 0.5 \cdot 3.5 \cdot 0.7 \cdot -\frac{3.5}{3})}{84.525} = -1.556 \quad \text{m}$$

Calculation of active pressure. In the first level is same active pressure as in the verification of the whole wall (part 1.2). Centroids of all forces are recalculated.

▷ Vertical geostatic stress σ_{z2} in the second level:

$$\sigma_{z2} = 27.0 + 16.561 \cdot 2 = 60.121 \quad \text{kPa}$$

▷ Active pressure σ_{a2b} at the end of second level (value at the beginning is same, i.e. $\sigma_{a2a} = 4.121$ kPa):

$$\sigma_{a2b} = 0.402 \cdot 60.121 - 2 \cdot 5.714 \cdot 0.588 = 17.424 \quad \text{kPa}$$

▷ Resultant force of the active pressure S_{a2} and horizontal, resp. vertical component:

$$S_{a2} = 0.5 \cdot (17.424 - 4.121) \cdot 2 + 4.121 \cdot 2 = 21.545 \quad \text{kN/m}$$

$$S_{ax2} = S_{a2} \cdot \cos \delta_{d2} = 21.545 \cdot \cos 13.636 = 20.938 \quad \text{kN/m}$$

$$S_{az2} = S_{a2} \cdot \sin \delta_{d2} = 21.545 \cdot \sin 13.636 = 5.079 \quad \text{kN/m}$$

▷ Points of action of resultant forces:

$$x_1 = 1.400 \quad \text{m} \qquad z_1 = -2.84 + 0.8 = -2.040 \quad \text{m}$$

$$x_2 = 1.400 \quad \text{m}$$

$$z_2 = -\frac{0.5 \cdot 4.121 \cdot 2^2 + \frac{1}{6} \cdot (17.424 - 4.121) \cdot 2^2}{4.121 \cdot 2 + 0.5 \cdot (17.424 - 4.121) \cdot 2} = -0.794 \quad \text{m}$$

▷ Total resultant force of the active pressure S_a and horizontal, resp. vertical component:

$$S_{ax} = 20.989 \quad \text{kN/m} \qquad S_{az} = 5.092 \quad \text{kN/m} \qquad S_a = 21.598 \quad \text{kN/m}$$

▷ Point of action of resultant force S_a:

$$x = 1.400 \quad \text{m} \qquad z = \frac{-2.040 \cdot 0.052 - 0.794 \cdot 20.938}{21.598} = -0.797 \quad \text{m}$$

Calculation of water pressure. Water pressure grows with height ($h = 2$ m).

▷ Horizontal water pressure σ_w in the level of analysed cross-section:

$$\sigma_w = \gamma_w \cdot h = 10 \cdot 2 = 20.000 \quad \text{kPa}$$

▷ Resultant force of the water pressure S_w:

$$S_w = \frac{1}{2} \cdot \sigma_w \cdot h = \frac{1}{2} \cdot 20 \cdot 2 = 20.000 \quad \text{kN/m}$$

▷ Point of action of the resultant force:

$$x = 2.300 \quad \text{m}$$

$$z = -\frac{2}{3} = -0.667 \quad \text{m}$$

Verification of shear strength. Shear and normal force, bending moment and shear strength of cross-section are calculated.

▷ Design shear force:

$$V_{Ed} = 20.989 + 20 = 40.989 \quad \text{kN/m}$$

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

▷ Design normal force:

$$N_{Ed} = 84.525 + 5.092 = 89.617 \quad \text{kN/m}$$

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

▷ Area of cross-section:

$$A_{cc} = b \cdot h = 1 \cdot 1.4 = 1.4 \quad \text{m}^2$$

▷ Stress in cross-section area:

$$\sigma_{cp} = \frac{N_{Ed}}{A_{cc} \cdot 1000} = \frac{89.617}{1.4 \cdot 1000} = 0.064 \quad \text{MPa}$$

▷ Design strength of concrete in compression (coefficients $\alpha_{cc.pl} = 0.8$, $\gamma_c = 1.5$):

$$f_{cd} = \alpha_{cc.pl} \cdot \frac{f_{ck}}{\gamma_c} = 0.8 \cdot \frac{20}{1.5} = 10.667 \quad \text{MPa}$$

▷ Lower value of characteristic strength of concrete in tension:

$$f_{ctk.005} = 0.7 \cdot (0.3 \cdot f_{ck}^{\frac{2}{3}}) = 0.7 \cdot (0.3 \cdot 20^{\frac{2}{3}}) = 1.547 \quad \text{MPa}$$

▷ Design strength of concrete in tension (coefficients $\alpha_{ct.pl} = 0.8$, $\gamma_c = 1.5$):

$$f_{ctd} = \alpha_{ct.pl} \cdot \frac{f_{ctk.005}}{\gamma_c} = 0.8 \cdot \frac{1.547}{1.5} = 0.825 \quad \text{MPa}$$

▷ Limit stress:

$$\sigma_{c.lim} = f_{cd} - 2 \cdot \sqrt{f_{ctd} \cdot (f_{cd} + f_{fctd})}$$

$$\sigma_{c.lim} = 10.667 - 2 \cdot \sqrt{0.825 \cdot (10.667 + 0.825)} = 4.508 \quad \text{MPa}$$

▷ Shear strength:

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

$$f_{cvd} = \sqrt{0.825^2 + 0.064 \cdot 0.825 - \left(\frac{0}{2}\right)^2} = 0.857 \quad \text{MPa}$$

▷ Design shear strength ($k = 1.5$):

$$V_{Rd} = \frac{f_{cvd} \cdot A_{cc}}{k} = \frac{0.857 \cdot 1.4}{1.5} = 799.523 \quad \text{kN/m}$$

Result from program GEO5 Gravity Wall: $V_{Rd} = 799.37$ kN/m

▷ Usage:

$$V_u = \frac{V_{Ed}}{V_{Rd}} \cdot 100 = \frac{40.989}{799.523} \cdot 100 = 5.1 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 5.1$ % O.K.

Verification of cross-section loaded by bending moment and normal force. Moment turns around the cross-section centroid.

▷ Design bending moment:

$$M_{Ed} = -84.525 \cdot (0.856 - 0.7) - 5.092 \cdot 0.7 + 20.989 \cdot 0.797 + 20 \cdot 0.667 = 13.355 \quad \text{kN/m}$$

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

▷ Normal force eccentricity:

$$e = \frac{M_{Ed}}{N_{Ed}} = \frac{13.355}{89.617} = 0.149 \quad \text{m}$$

$$0.9 \cdot \frac{h}{2} = 0.9 \cdot \frac{1.4}{2} = 0.63 \quad \text{m} \quad > \quad e = 0.149 \quad \text{m}$$

▷ Effective height:

$$\chi = h - 2 \cdot e = 1.4 - 2 \cdot 0.149 = 1.102 \quad \text{m}$$

▷ Design normal strength ($\eta = 1.0$):

$$N_{Rd} = \chi \cdot \eta \cdot f_{cd} = 1.102 \cdot 1 \cdot 10.667 = 11754.239 \quad \text{kN/m}$$

Result from program GEO5 Gravity Wall: $N_{Rd} = 11758.56 \quad \text{kN/m}$

▷ Usage:

$$V_u = \frac{N_{Ed}}{N_{Rd}} \cdot 100 = \frac{89.617}{11754.239} \cdot 100 = 0.8 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 0.8 \quad \% \quad \text{O.K.}$

1.5 Verification of the wall - influence of earthquake

Second stage of calculation shows the same wall with the influence of earthquake. Calculation of earthquake effects is made according to Mononobe-Okabe theory [2], [3]. Factor of horizontal acceleration is $k_h = 0.05$ (inertia force acts horizontally in unfavorable direction) and factor of vertical acceleration $k_v = -0.04$ (inertia force acts downwards). Coefficients of reduction of soil parameters and coefficient of overall stability of construction are equal to one ($\gamma_{m\varphi} = \gamma_{mc} = \gamma_s = 1.0$). Therefore design soil properties are same as characteristic values in Tab. 1.

Calculation of weight of the wall. Weight of the wall $W = 116.484$ kN/m (see part 1.2) is increased by weight force from earthquake.

▷ Horizontal and vertical component of weight force from earthquake:

$$W_{eq.x} = k_h \cdot W = 0.05 \cdot 116.484 = 5.824 \quad \text{kN/m}$$

$$W_{eq.z} = -k_v \cdot W = 0.04 \cdot 116.484 = 4.659 \quad \text{kN/m}$$

Calculation of front face resistance. Pressure at rest on front face of the wall is considered same as in part 1.2, i.e. resultant force is $S_r = 0.430$ kN/m.

Calculation of active pressure. Active pressure σ_a and resultant force S_a are calculated similarly as in the calculation without earthquake (part 1.2), geostatic stress σ_z is same, i.e. $\sigma_{z1} = 27.000$ kPa and $\sigma_{z2} = 77.179$ kPa.

▷ Coefficients of the active pressure in both levels:

$$K_{a1} = \frac{\cos^2 26.50}{\cos 15 \cdot \left[1 + \sqrt{\frac{\sin(26.5+15)\cdot\sin(26.5-5.711)}{\cos 15\cdot\cos(-5.711)}}\right]^2} = 0.371$$

$$K_{ac1} = \frac{\cos 26.5 \cdot \cos 5.711 \cdot \cos 15 \cdot (1 + \tan 0 \cdot \tan 5.711)}{(1 + \sin(26.5 + 15 - 5.711)) \cdot \cos 15} = 0.562$$

$$K_{a2} = \frac{\cos^2 27}{\cos 15 \cdot \left[1 + \sqrt{\frac{\sin(27+15)\cdot\sin(27-5.557)}{\cos 15\cdot\cos(-5.557)}}\right]^2} = 0.363$$

$$K_{ac2} = \frac{\cos 27 \cdot \cos 5.557 \cdot \cos 15 \cdot (1 + \tan 0 \cdot \tan 5.557)}{(1 + \sin(27 + 15 - 5.557)) \cdot \cos 15} = 0.556$$

▷ Depth h_0 in the first layer of soil MS, where is neutral active pressure ($\sigma_a = 0$ kPa):

$$h_0 = \frac{2 \cdot c_1 \cdot K_{ac1}}{\gamma_1 \cdot K_{a1}} = \frac{2 \cdot 12 \cdot 0.562}{18 \cdot 0.371} = 2.019 \quad \text{m} \quad > \quad h_1 = 1.5 \quad \text{m}$$

Active pressure is in the whole first level equal to zero.

▷ Active pressure σ_a in the second layer of soil SC:

$$\sigma_{a2a} = K_{a2} \cdot \sigma_{z1} - 2 \cdot c_2 \cdot K_{ac2} = 0.363 \cdot 27 - 2 \cdot 8 \cdot 0.556 = 0.903 \quad \text{kPa}$$

$$\sigma_{a2b} = K_{a2} \cdot \sigma_{z2} - 2 \cdot c_2 \cdot K_{ac2} = 0.363 \cdot 77.179 - 2 \cdot 8 \cdot 0.556 = 19.126 \quad \text{kPa}$$

▷ Total resultant force of the active pressure S_a and horizontal, resp. vertical component:

$$S_a = 0.5 \cdot (\sigma_{a2b} - \sigma_{a2a}) \cdot h_2 + \sigma_{a2a} \cdot h_2$$

$$S_a = 0.5 \cdot (19.126 - 0.903) \cdot 3.03 + 0.903 \cdot 3.03 = 30.344 \quad \text{kN/m}$$

$$S_{ax} = S_a \cdot \cos\delta_2 = 30.344 \cdot \cos 15 = 29.310 \quad \text{kN/m}$$

$$S_{az} = S_a \cdot \sin\delta_2 = 30.344 \cdot \sin 15 = 7.854 \quad \text{kN/m}$$

▷ Point of action of the resultant force:

$$x = 2.300 \quad \text{m}$$

$$z = -\frac{\frac{1}{6} \cdot 3.03^2 \cdot (19.126 - 0.903) + \frac{1}{2} \cdot 3.03^2 \cdot 0.903}{\frac{1}{2} \cdot 3.03 \cdot (19.126 - 0.903) + 3.03 \cdot 0.903} + 0.23 = -0.826 \quad \text{m}$$

Increase of active pressure caused by earthquake. Earthquake increases the effect of active pressure.

▷ Seismic inertia angle in the first layer of soil MS:

$$\psi_1 = \arctan\frac{k_h}{1 - k_v} = \arctan\frac{0.05}{1 + 0.04} = 2.752^\circ$$

▷ Seismic inertia angle in the second layer of soil SC, where is restricted water:

$$\psi_2 = \arctan\frac{\gamma_{sat} \cdot k_h}{(\gamma_{sat} - \gamma_w) \cdot (1 - k_v)} = \arctan\frac{20.5 \cdot 0.05}{(20.5 - 10) \cdot (1 + 0.04)} = 5.362^\circ$$

▷ Coefficients K_{ae} for the active pressure in both levels:

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

$$K_{ae1} = \frac{\cos^2(26.5 - 2.752)}{\cos 2.752 \cdot \cos(2.752 + 15) \cdot \left[1 + \sqrt{\frac{\sin(26.5+15)\cdot\sin(26.5-2.752-5.711)}{\cos(2.752+15)\cdot\cos(5.711)}}\right]^2} = 0.410$$

$$K_{ae2} = \frac{\cos^2(27 - 5.362)}{\cos 5.362 \cdot \cos(5.362 + 15) \cdot \left[1 + \sqrt{\frac{\sin(27+15)\cdot\sin(27-5.362-5.557)}{\cos(5.362+15)\cdot\cos(5.557)}}\right]^2} = 0.443$$

▷ Normal stress σ_d for calculation of earthquake effects (stress grows from the bottom of the wall - σ_{d2} is in the footing bottom level and σ_{d0} is in the terrain level):

$$\sigma_{d2} = 0 \quad \text{kPa}$$

$$\sigma_{d1} = \gamma_2 \cdot h_2 \cdot (1 - k_v) = 16.561 \cdot 3.03 \cdot (1 + 0.04) = 52.186 \quad \text{kPa}$$

$$\sigma_{d0} = \sigma_{d1} + \gamma_1 \cdot h_1 \cdot (1 - k_v) = 52.186 + 18 \cdot 1.5 \cdot (1 + 0.04) = 80.266 \quad \text{kPa}$$

▷ Increase of the active pressure from earthquake effects in the first layer of soil MS:

$$\sigma_{ae0} = \sigma_{d0} \cdot \frac{(K_{ae1} - K_{a1})}{1 - k_v} = 80.266 \cdot \frac{(0.410 - 0.371)}{1 + 0.04} = 3.014 \quad \text{kPa}$$

$$\sigma_{ae1a} = \sigma_{d1} \cdot \frac{(K_{ae1} - K_{a1})}{1 - k_v} = 52.186 \cdot \frac{(0.410 - 0.371)}{1 + 0.04} = 1.959 \quad \text{kPa}$$

▷ Increase of the active pressure from earthquake effects in the second layer of soil SC:

$$\sigma_{ae1b} = \sigma_{d1} \cdot \frac{(K_{ae2} - K_{a2})}{1 - k_v} = 52.186 \cdot \frac{(0.443 - 0.363)}{1 + 0.04} = 4.003 \quad \text{kPa}$$

$$\sigma_{ae2} = 0 \quad \text{kPa}$$

▷ Resultant forces of increase of the active pressure S_{ae} and horizontal, resp. vertical components:

$$S_{ae1} = 0.5 \cdot (\sigma_{ae0} - \sigma_{ae1a}) \cdot h_1 + \sigma_{ae1a} \cdot h_1$$

$$S_{ae1} = 0.5 \cdot (3.014 - 1.959) \cdot 1.5 + 1.959 \cdot 1.5 = 3.730 \quad \text{kN/m}$$

$$S_{aex1} = S_{ae1} \cdot \cos\delta_1 = 3.730 \cdot \cos 15 = 3.603 \quad \text{kN/m}$$

$$S_{aez1} = S_{ae1} \cdot \sin\delta_1 = 3.730 \cdot \sin 15 = 0.965 \quad \text{kN/m}$$

$$S_{ae2} = 0.5 \cdot \sigma_{ae1b} \cdot h_2 = 0.5 \cdot 4.003 \cdot 3.03 = 6.064 \quad \text{kN/m}$$

$$S_{aex2} = S_{ae2} \cdot \cos\delta_2 = 6.064 \cdot \cos 15 = 5.857 \quad \text{kN/m}$$

$$S_{aez2} = S_{ae2} \cdot \sin\delta_2 = 6.064 \cdot \sin 15 = 1.569 \quad \text{kN/m}$$

▷ Points of action of resultant forces:

$$x_1 = 2.300 \quad \text{m}$$

$$z_1 = -2.8 - \frac{\frac{1}{2} \cdot 1.5^2 \cdot 1.959 + \frac{1}{3} \cdot 1.5^2 \cdot (3.014 - 1.959)}{1.5 \cdot 1.959 + 0.5 \cdot 1.5 \cdot (3.014 - 1.959)} = -3.603 \quad \text{m}$$

$$x_2 = 2.300 \quad \text{m}$$

$$z_2 = 0.23 - \frac{2}{3} \cdot 3.03 = -1.790 \quad \text{m}$$

▷ Total resultant force of increase of the active pressure S_{ae} and horizontal, resp. vertical component:

$$S_{aex} = \sum_{i=1}^{2} S_{aexi} = 3.603 + 5.857 = 9.460 \quad \text{kN/m}$$

$$S_{aez} = \sum_{i=1}^{2} S_{aezi} = 0.965 + 1.569 = 2.535 \quad \text{kN/m}$$

$$S_{ae} = \sqrt{S_{aex}^2 + S_{aez}^2} = \sqrt{9.460^2 + 2.535^2} = 9.794 \quad \text{kN/m}$$

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

$$x = 2.300 \quad \text{m}$$

$$z = \frac{\sum_{i=1}^{2} S_{aexi} \cdot z_i}{S_{aex}} = \frac{-12.981 - 10.485}{9.460} = -2.480 \quad \text{m}$$

Calculation of water pressure. Water pressure is same as in the verification of the whole wall (part 1.2), i.e. resultant force of the water pressure is $S_w = 33.330$ kN/m.

Checking for overturning stability. The moment rotates around the beginning of system of coordinates (left bottom corner of the footing).

▷ Resisting moment M_r:

$$M_r = (116.484 + 4.659) \cdot 1.601 + (7.854 + 2.535) \cdot 2.3 = 217.810 \quad \text{kNm/m}$$

Result from program GEO5 Gravity Wall: $M_r = 217.83 \quad \text{kNm/m}$

▷ Driving moment M_o:

$$M_o = -0.43 \cdot 0.2 + 29.31 \cdot 0.826 + 9.46 \cdot 2.48 + 33.33 \cdot 1.057 + 5.824 \cdot 1.817 = 93.377 \quad \text{kNm/m}$$

Result from program GEO5 Gravity Wall: $M_o = 93.43 \quad \text{kNm/m}$

▷ Usage:

$$V_u = \frac{M_o}{M_r} \cdot 100 = \frac{93.377}{217.810} \cdot 100 = 42.9 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 42.9$ % O.K.

Checking for slip. Slip in the inclined footing bottom is checked. (Fig. 4).

▷ Total vertical and horizontal forces F_{vert} and F_{hor}:

$$F_{vert} = 116.484 + 4.659 + 7.854 + 2.535 = 131.531 \quad \text{kN/m}$$

$$F_{hor} = -0.430 + 29.310 + 9.460 + 33.330 + 5.824 = 77.494 \quad \text{kN/m}$$

▷ Normal force in the footing bottom (inclination of footing bottom $\alpha_b = 5.711°$, see Fig. 4):

$$N = 131.531 \cdot \cos 5.711 + 77.494 \cdot \sin 5.711 = 138.589 \quad \text{kN/m}$$

▷ Shear reaction in the footing bottom:

$$T = -131.531 \cdot \sin 5.711 + 77.494 \cdot \cos 5.711 = 64.022 \quad \text{kN/m}$$

▷ Eccentricity of the normal force (inclined width of the footing bottom $d = 2.311$ m):

$$e = \frac{d}{2} - \frac{M_r - M_o}{N} = \frac{2.311}{2} - \frac{217.810 - 93.43}{138.589} = 0.258 \quad \text{m}$$

▷ Maximal allowable eccentricity:

$$e_{alw} = \frac{d}{3} = \frac{2.311}{3} = 0.770 \quad \text{m} \quad > \quad e = 0.258 \quad \text{m} \quad \text{O.K.}$$

▷ Resisting force H_r:

$$H_r = 138.589 \cdot \tan 27 + 8 \cdot (2.311 - 2 \cdot 0.258) = 84.981 \quad \text{kN/m}$$

Result from program GEO5 Gravity Wall: $H_r = 85.07$ kN/m

▷ Driving force H_d:

$$H_d = T = 64.022 \quad \text{kN/m}$$

Result from program GEO5 Gravity Wall: $H_d = 64.05$ kN/m

▷ Usage:

$$V_u = \frac{H_d}{H_r} \cdot 100 = \frac{64.022}{84.981} \cdot 100 = 75.3 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 75.3 \quad \% \quad \text{O.K.}$

1.6 Bearing capacity of the foundation soil

Bearing capacity of the foundation soil is set as $R_d = 100$ kPa and is compared with stress in the inclined footing bottom.

▷ Usage - eccentricity:

$$V_u = \frac{e}{e_{alw}} \cdot 100 = \frac{0.258}{0.770} \cdot 100 = 33.5 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 33.1 \quad \% \quad \text{O.K.}$

▷ Stress in the footing bottom:

$$\sigma = \frac{N}{(d - 2 \cdot e)} = \frac{138.589}{(2.311 - 2 \cdot 0.258)} = 77.178 \quad \text{kPa}$$

Result from program GEO5 Gravity Wall: $\sigma = 76.72 \quad \text{kPa}$

▷ Usage:

$$V_u = \frac{\sigma}{R_d} \cdot 100 = \frac{77.178}{100} \cdot 100 = 77.2 \quad \% \quad \text{O.K.}$$

Result from program GEO5 Gravity Wall: $V_u = 76.7 \quad \% \quad \text{O.K.}$

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