Verification Analysis of the Slope Stability

Program: Slope Stability
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In this verification manual you will find hand-made verification analysis of the stability of slope and anchored slope in a permanent design situation. The results of the hand-made calculations are compared with the results from the GEO5 – Slope Stability program.

Terms of Reference:

In Figure 1, an example of a slope is shown. The slope has a height $H = 10.0\,m$ and is adjusted in 1:1.5 inclination. At the top of the slope is a load $f = 20\,kN/m^2$. The earth body is formed of sandy clay (CS). The properties of soil (effective values) are shown in Table 1. The calculation is divided into two stages. In the 1st stage the stability of the slope is calculated and in the 2nd stage the stability of an anchored slope is calculated. The slope stability is calculated using Fellenius/Petterson method and Bishop's simplified method (the circular slip surface). The verification methodology of the slope stability is done according to safety factors.

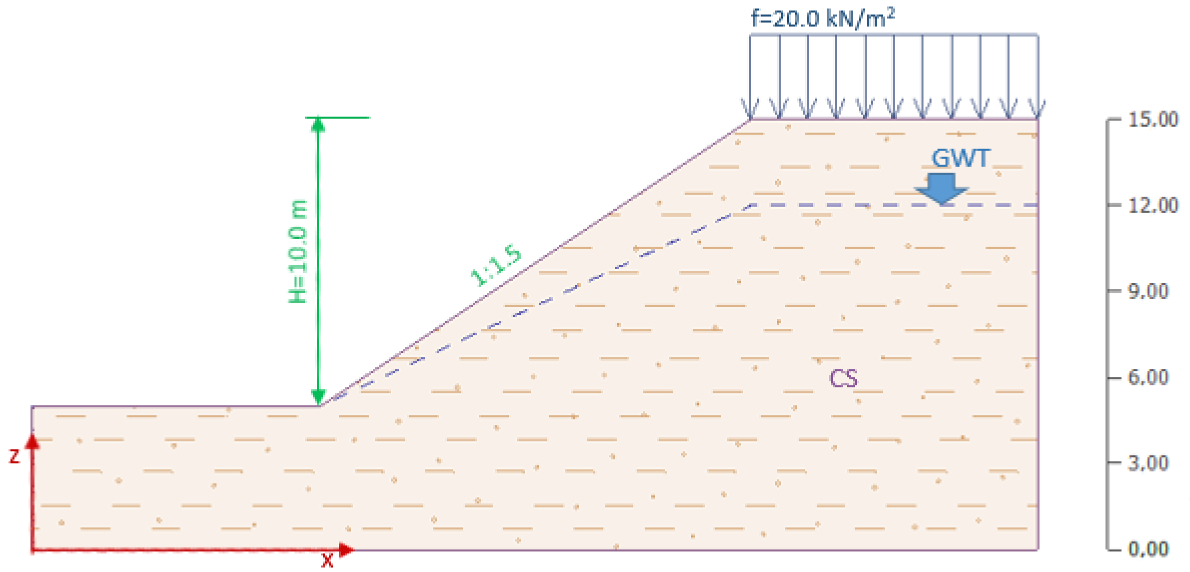

Figure 1 Slope - dimensions

Soil	Unit weight $\gamma\,[kN/m^3]$	Saturated unit weight $\gamma_{sat}\,[kN/m^3]$	Angle of internal friction $\varphi_{ef}\,[^\circ]$	Cohesion of soil $c_{ef}\,[kPa]$
CS	18.50	19.50	27.00	21.00

Table 1 Soil properties – effective values

1. Fellenius/Petterson Method

Verification of the Stability of the Slope

The slip surface was determined. In this case the slip surface is determined by a circle with its centre at point $O = [x, z] = [13.5279; 18.9443]$ and a radius $R = 15.00\ m$. Points Z_{sp} and K_{sp} indicate the beginning and end of the slip surface. The slope was divided into vertical blocks of width $b_i = 1.0\ m$. In Figure 2, a slope divided into 20 blocks is shown.

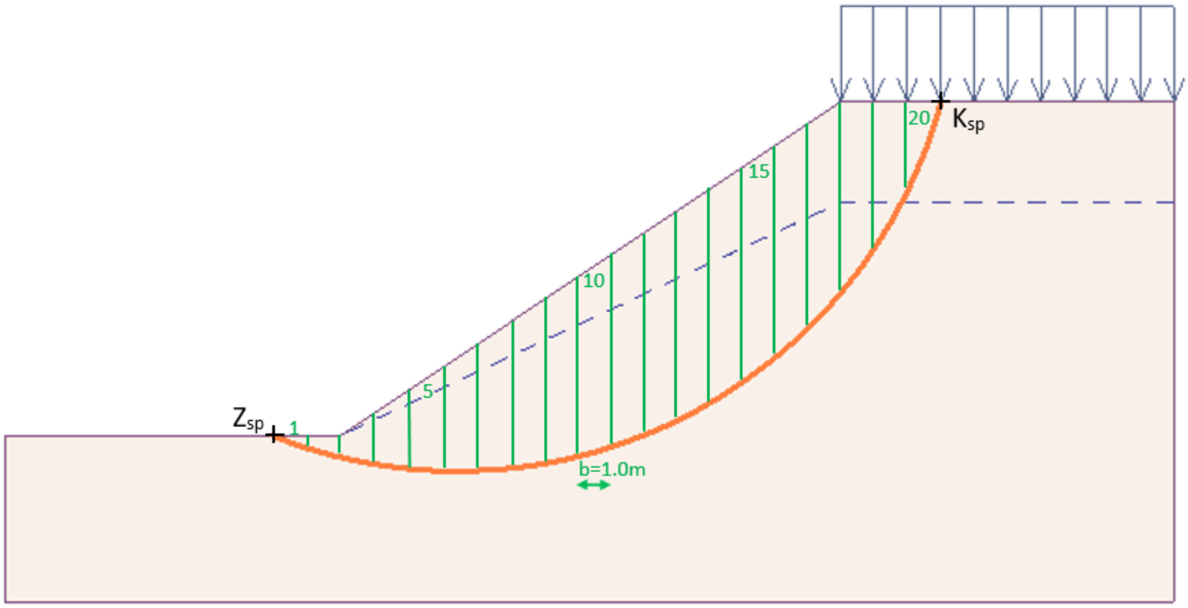

Figure 2 Slope – vertical blocks

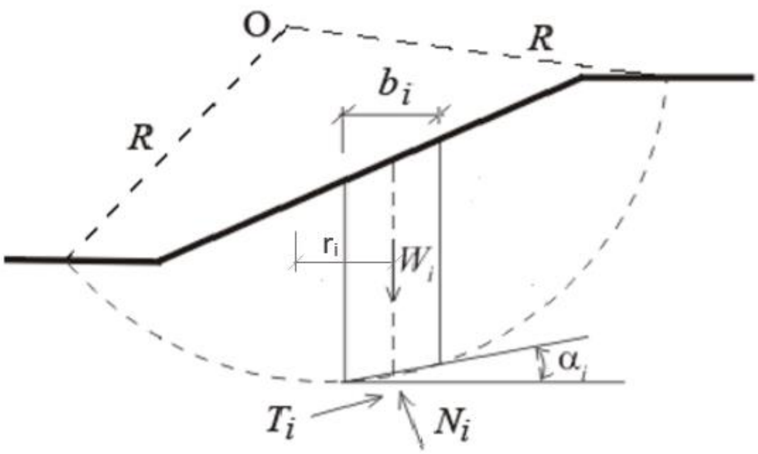

Figure 3 Static scheme of the block

Calculation of the weight of the individual blocks of the slope. The weight of the blocks of the earth body bounded by the slip surface are calculated. The overall calculation is shown in Table 2. An example of the calculation for block number 13 is done.

- Determination of the area above the ground water table (the area A) and under the ground water table (the area B):

  $A_{13} = 2.100\ m^2$

  $B_{13} = 4.2249\ m^2$

- Weight of the individual parts of the block:

  $A_{W,13} = A_{13} \cdot \gamma = 2.100 \cdot 18.50 = 38.8500\, kN/m$

  $B_{W,13} = B_{13} \cdot \gamma_{sat} = 4.2249 \cdot 19.50 = 82.3856\, kN/m$

- Weight force of the block:

  $W_{13} = A_{W,13} + B_{W,13} = 38.8500 + 82.3856 = 121.236\, kN/m$

- Calculation for all blocks:

Block	Area of the part		Width of the block	Weight of one part		Weight of the block	Load
	A_i $[m^2]$	B_i $[m^2]$	b_i $[m]$	$A_{W,i}$ $[kN/m]$	$B_{W,i}$ $[kN/m]$	W_i $[kN/m]$	f_i $[kN/m]$
1	0.0000	0.1780	1.000	0.000	3.471	3.471	0.000
2	0.0000	0.4955	1.000	0.000	9.662	9.662	0.000
3	0.1000	0.9714	1.000	1.850	18.942	20.792	0.000
4	0.3000	1.6095	1.000	5.550	31.385	36.935	0.000
5	0.5000	2.1787	1.000	9.250	42.485	51.735	0.000
6	0.7000	2.6807	1.000	12.950	52.274	65.224	0.000
7	0.9000	3.1158	1.000	16.650	60.758	77.408	0.000
8	1.1000	3.4836	1.000	20.350	67.930	88.280	0.000
9	1.3000	3.7828	1.000	24.050	73.765	97.815	0.000
10	1.5000	4.0109	1.000	27.750	78.212	105.963	0.000
11	1.7000	4.1644	1.000	31.450	81.206	112.656	0.000
12	1.9000	4.2381	1.000	35.150	82.643	117.793	0.000
13	2.1000	4.2249	1.000	38.850	82.386	121.236	0.000
14	2.3000	4.1148	1.000	42.550	80.239	122.789	0.000
15	2.5000	3.8937	1.000	46.250	75.927	122.177	0.000
16	2.7000	3.5409	1.000	49.950	69.048	118.998	0.000
17	2,.9000	3.0240	1.000	53.650	58.968	112.618	0.000
18	3.0000	2.0544	1.000	55.500	40.061	95.561	20.000
19	2.9692	0.5721	1.000	54.930	11.156	66.086	20.000
20	1.4192	0.0000	1.000	26.255	0.000	26.255	20.000

Table 2 Weight and forces of the load

Determination of the inclination of the slip surface of the individual blocks and calculation of the pore pressure. To simplify the hand-made calculation the circle slip surfaces of the individual blocks have been replaced by lines. The inclination of the slip surface is determined by the angle between the slip surface and the horizontal plane.

The height of the ground water table must be determined for the calculation of the pore pressure. The height of the ground water table h_i is considered to the axis of the block. The unit weight of water is $\gamma_w = 10.00\ kN/m^3$. The heights of the ground water table on the left and right side of the block must be determined for the calculation of the horizontal forces of the pore pressure. The overall calculation is shown in Table 3. An example of the calculation for block number 13 is done.

- Inclination of the slip surface:

$$\alpha_{13} = 27.7192\,°$$

- Length of the slip surface:

$$l_{13} = \frac{b_{13}}{\cos(\alpha_{13})} = \frac{1.000}{\cos(27.7192)} = 1.130\ m$$

- Inclination of the ground water table:

$$\alpha_{w,13} = 25.0169°$$

- Height of the ground water table:

$$h_{13} = 4.2369\ m$$

- Calculation of the reduced height of the ground water table:

$$h_{r,13} = h_{13} \cdot \cos(\alpha_{w,13})^2 = 4.2369 \cdot \cos(25.0169)^2 = 3.479\,m$$

- Calculation of the pore pressure:

$$u_{13} = \gamma_w \cdot h_{r,13} = 10.00 \cdot 3.479 = 34.790\,kPa$$

- Calculation of the horizontal forces of the pore pressure:

$$U_{HL,13} = \frac{\left[h_{L,13} \cdot \cos(\alpha_{w,13})\right]^2 \cdot \gamma_w}{2} = \frac{\left[4.2543 \cdot \cos(25.0169)\right]^2 \cdot 10}{2} = 74.312\ kN/m$$ - left side

$$U_{HP,13} = \frac{\left[h_{P,13} \cdot \cos(\alpha_{w,13})\right]^2 \cdot \gamma_w}{2} = \frac{\left[4.1955 \cdot \cos(25.0169)\right]^2 \cdot 10}{2} = 72.272\ kN/m$$ - right side

- Calculation for all blocks:

Block	Inclination of the slip surface	Length of the slip surface	Ground water table			Pore pressure
			Inclination of the ground water table	Height of the ground water table	Reduced height of the ground water table	
	α_i [°]	l_i [m]	$\alpha_{w,i}$ [°]	h_i [m]	$h_{r,i}$ [m]	u_i [kPa]

1	-19.5956	1.061	0.0000	0.1880	0.188	1.880
2	-15.5860	1.038	0.0000	0.5048	0.505	5.050
3	-11.6525	1.021	25.0169	0.9803	0.805	8.050
4	-7.7741	1.009	25.0169	1.6180	1.329	13.290
5	-3.9314	1.002	25.0169	2.1871	1.796	17.960
6	0.1065	1.000	25.0169	2.6890	2.208	22.080
7	3.6119	1.002	25.0169	3.1242	2.566	25.660
8	7.5592	1.009	25.0169	3.4922	2.868	28.680
9	11.4351	1.020	25.0169	3.7917	3.114	31.140
10	15.3650	1.037	25.0169	4.0202	3.301	33.010
11	19.3709	1.060	25.0169	4.1744	3.428	34.280
12	23.4785	1.090	25.0169	4.2489	3.489	34.890
13	27.7192	1.130	25.0169	4.2369	3.479	34.790
14	32.1331	1.181	25.0169	4.1285	3.390	33.900
15	36.7741	1.248	25.0169	3.9099	3.211	32.110
16	41.7186	1.340	25.0169	3.5609	2.924	29.240
17	47.0841	1.469	25.0169	3.0504	2.505	25.050
18	53.0703	1.664	0.0000	2.0928	2.093	20.930
19	60.0828	2.005	0.0000	0.5872	0.587	5.870
20	69.3348	2.834	0.0000	0.0000	0.000	0.000

Table 3 Inclinations and lengths of the slip surfaces and pore pressures

Block	Left side of the block		Right side of the block	
	$h_{L,i}$ $[m]$	$U_{HL,i}$ $[kN/m]$	$h_{R,i}$ $[m]$	$U_{HR,i}$ $[kN/m]$
1	0.0000	0.000	0.3560	0.634
2	0.3560	0.634	0.6530	2.132
3	0.6530	2.132	1.3079	7.023
4	1.3079	7.023	1.9110	14.994
5	1.9110	14.994	2.4464	24.573
6	2.4464	24.573	2.9150	34.888
7	2.9150	34.888	3.3166	45.164
8	3.3166	45.164	3.6506	54.718
9	3.6506	54.718	3.9150	62.931
10	3.9150	62.931	4.1069	69.252
11	4.1069	69.252	4.2220	73.188
12	4.2220	73.188	4.2543	74.312
13	4.2543	74.312	4.1955	72.272
14	4.1955	72.272	4.0341	66.818
15	4.0341	66.818	3.7533	57.840
16	3.7533	57.840	3.3284	45.485
17	3.3284	45.485	2.7196	30.368
18	2.7196	30.368	1.3891	9.648
19	1.3891	9.648	0.0000	0.000

20	0.0000	0.000	0.0000	0.000

Table 4 Horizontal forces of the pore pressure

Calculation of the sliding moment. The weight of the individual blocks including forces of the load act on the horizontal arm from axis of the block to the centre of the circular slip surface (to the point O). The arms of the forces are calculated from the beginning of the slip surface ($Z_{sp} = [x, z] = [8.00; 5.00]$). The overall calculation is in Table 5. An example of the calculation for block number 13 is done.

- Calculation of the moment arm:

$$r_{a,13} = X_{zsp} - X_O + \left(i \cdot b - \frac{b}{2} \right) = 8.0000 - 13.5729 + \left(13 \cdot 1.0 - \frac{1.0}{2} \right) = 6.972\ m$$

- Calculation of the sliding moment:

$$M_{a,13} = (W_{13} + f_{13}) \cdot r_{a,13} = (121.236 + 0.000) \cdot 6.972 = 845.257\ kNm/m$$

- Calculation for all blocks:

Block	Sliding moment $r_{a,i}$ $[m]$	Sliding moment $M_{a,i}$ $[kNm/m]$	Block	Sliding moment $r_{a,i}$ $[m]$	Sliding moment $M_{a,i}$ $[kNm/m]$
1	-5.028	-17.452	11	4.972	560.126
2	-4.028	-38.919	12	5.972	703.460
3	-3.028	-62.958	13	6.972	845.257
4	-2.028	-74.904	14	7.972	978.874
5	-1.028	-53.184	15	8.972	1096.172
6	-0.028	-1.826	16	9.972	1186.648
7	0.972	75.241	17	10.972	1235.645
8	1.972	174.088	18	11.972	1383.496
9	2.972	290.706	19	12.972	1116.708
10	3.972	420.885	20	13.972	646.275

Table 5 Sliding moments

- Resultant sliding moment:

$$M_a = \sum_{i=1}^{20} M_{a,i} = 10464.338\ kNm/m$$

Result from the GEO5 – Slope Stability program: $M_a = 10447.88\ kNm/m$

- Resultant active force:

$$F_a = \frac{\sum_{i=1}^{20} M_{a,i}}{R} = \frac{10464.338}{15.00} = 697.623\ kN/m$$

Result from the GEO5 – Slope Stability program: $F_a = 696.53\ kN/m$

Calculation of the resisting moment. Normal forces N_i of the individual blocks must be calculated. The normal force acts upright to the slip surface. The overall calculation is shown in Table 6. An example of the calculation for block 13 is done.

- Calculation of the safety factor FS :

$$FS = \frac{M_p}{M_a}$$

- Calculation of the normal force:

$$N_{13} = (W_{13} + f_{13}) \cdot \cos(\alpha_{13}) - u_{13} \cdot l_{13} + (U_{HL,13} - U_{HR,13}) \cdot \sin(\alpha_{13})$$

$$N_{13} = (121.236 + 0.000) \cdot \cos(27.7192) - 34.790 \cdot 1.130 + (74.312 - 72.272) \cdot \sin(27.7192) = 68.959\ kN/m$$

- Calculation of the resisting moment:

$$M_{p,13} = [c_{13} \cdot l_{13} + N_{13} \cdot \tan(\varphi)] \cdot R = [21.00 \cdot 1.130 + 68.959 \cdot \tan(27.00)] \cdot 15.00 = 882.995\ kNm/m$$

- Calculation for all blocks:

Block	Normal force	Resisting moment	Block	Normal force	Resisting moment
	N_i $[kN/m]$	$M_{p,i}$ $[kNm/m]$		N_i $[kN/m]$	$M_{p,i}$ $[kNm/m]$
1	1.488	345.588	11	68.636	858.477
2	4.467	361.111	12	69.563	875.012
3	13.132	421.981	13	68.959	882.995
4	24.264	503.282	14	66.845	882.903
5	34.274	577.582	15	63.166	875.890
6	43.125	644.599	16	57.863	864.340
7	50.906	704.699	17	50.957	852.193
8	57.318	755.910	18	51.169	915.239
9	62.482	798.843	19	39.528	933.683
10	66.269	833.141	20	16.324	1017.472

Table 6 Normal forces and resisting moments

- Resultant resisting moment:

$$M_p = \sum_{i=1}^{20} M_{p,i} = 14904.940 \; kNm/m$$

Result from the GEO5 – Slope Stability program: $M_p = 14936.16 \; kNm/m$

- Resultant passive force:

$$F_p = \frac{\sum_{i=1}^{20} M_{p,i}}{R} = \frac{14904.940}{15.00} = 993.663 \; kN/m$$

Result from the GEO5 – Slope Stability program: $F_p = 995.74 \; kN/m$

- Calculation of the safety factor:

$$FS = \frac{M_p}{M_a} = \frac{14904.940}{10464.338} = 1.424$$, NOT OK

Result from the GEO5 – Slope Stability program: $FS = 1.43$ **, NOT OK**

Verification of the Stability of Anchored Slope

In Figure 4, an example of anchored slope in the 2nd stage is shown. The anchor force is $F_A = 200.00 \; kN$ and the spacing is $b_A = 2.00 \; m$. The position of the anchor head is $H_{anchor} = [x, z] = [16.00; 9.00]$. The anchor head is on block number 9.

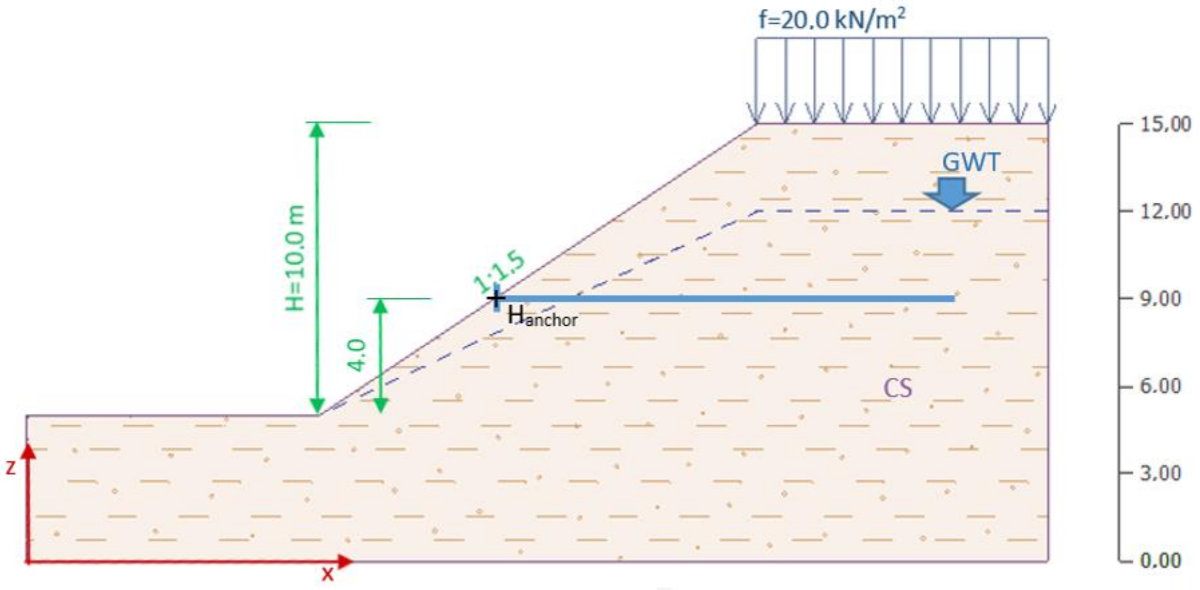

Figure 4 Anchored slope - dimensions

Calculation of the sliding moment. The anchor acts as a passive element, which means that active moments will be the same as in the 1st stage.

- Resultant sliding moment:

$$M_a = \sum_{i=1}^{20} M_{a,i} = 10464.338 \; kNm/m$$

Result from the GEO5 – Slope Stability program: $M_a = 10447.88 \; kNm/m$

- Resultant active force:

$$F_a = \frac{\sum_{i=1}^{20} M_{a,i}}{R} = \frac{10464.338}{15.00} = 697.623 \; kN/m$$

Result from the GEO5 – Slope Stability program: $F_a = 696.53 \; kN/m$

Calculation of the resisting moment. The normal forces N_i of the individual blocks must be calculated. The normal force acts perpendicular to the slip surface. Normal force on block number 9 is influenced by the anchor force. The overall calculation is shown in Table 7. An example of the calculation for block 13 is done.

- Anchor force at 1 m:

$$F_A^{'} = \frac{F_A}{b_A} = \frac{200.00}{2.00} = 100.00 \; kN/m$$

- Calculation of the arm of the anchor force:

$$r_A = Z_O - Z_{anchor} = 18.944 - 9.000 = 9.944 \; m$$

- Resisting moment of the anchor:

$$M_{p,A} = F_A^{'} \cdot r_A = 100.00 \cdot 9.944 = 994.400 \; kNm/m$$

- Calculation of the safety factor FS :

$$FS = \frac{M_p}{M_a}$$

- Calculation of the normal force:

$$N_{13} = (W_{13} + f_{13}) \cdot \cos(\alpha_{13}) - u_{13} \cdot l_{13} + (U_{HL,13} - U_{HR,13}) \cdot \sin(\alpha_{13})$$

$$N_{13} = (121.236 + 0.000) \cdot \cos(27.7192) - 34.790 \cdot 1.130 + (74.312 - 72.272) \cdot \sin(27.7192) = 68.959 \; kN/m$$

- Calculation of the effect of the anchor force (block number 9):

$$N_{A,9} = F'_A \cdot \sin(\alpha_9) = 100.000 \cdot \sin(11.4351) = 19.826 \, kN/m$$

- Calculation of the resisting moment:

$$M_{p,13} = [c_{13} \cdot l_{13} + N_{13} \cdot \tan(\varphi)] \cdot R = [21.00 \cdot 1.130 + 68.959 \cdot \tan(27.00)] \cdot 15.00 = 882.995 \; kNm/m$$

- Calculation for all blocks:

Block	Normal force N_i $[kN/m]$	Resisting moment $M_{p,i}$ $[kNm/m]$	Block	Normal force N_i $[kN/m]$	Resisting moment $M_{p,i}$ $[kNm/m]$
1	1.488	345.588	11	68.636	858.477
2	4.467	361.111	12	69.563	875.012
3	13.132	421.981	13	68.959	882.995
4	24.264	503.282	14	66.845	882.903
5	34.274	577.582	15	63.166	875.890
6	43.125	644.599	16	57.863	864.340
7	50.906	704.699	17	50.957	852.193
8	57.318	755.910	18	51.169	915.239
9	82.308	950.370	19	39.528	933.683
10	66.269	833.141	20	16.324	1017.472

Table 7 Normal forces and resisting moments

- Resultant resisting moment:

$$M_p = \sum_{i=1}^{20} M_{p,i} + M_{p,A} = 15056.467 + 994.400 = 16050.867 \; kNm/m$$

Result from the GEO5 – Slope Stability program: $M_p = 16081.40 \; kNm/m$

- Resultant passive force:

$$F_p = \frac{\sum_{i=1}^{20} M_{p,i} + M_{p,A}}{R} = \frac{1605.867}{15.00} = 1070.058 \; kN/m$$

Result from the GEO5 – Slope Stability program: $F_p = 1072.09 \; kN/m$

- Calculation of the safety factor:

$$FS = \frac{M_p}{M_a} = \frac{16050.867}{10464.338} = 1.534$$, SATISFACTORY

Result from the GEO5 – Slope Stability program: $FS = 1.54$ **, SATISFACTORY**

2. Bishop's Simplified Method

Verification of the Stability of the Slope

The slip surface is the same as in the first calculation using the Fellenius/Petterson method (Figure 2). The calculation of the weight of the individual blocks is shown in Table 2.

Determination of the inclination of the slip surface of the individual blocks and calculation of the pore pressure. To simplify the hand-made calculation the circular slip surfaces of the individual blocks have been replaced by lines. The inclination of the slip surface is determined by the angle between the slip surface and the horizontal plane.

The height of the ground water table must be determined for the calculation of the pore pressure. The height of the ground water table h_i is considered to the axis of the block. The unit weight of water is $\gamma_w = 10.00\ kN/m^3$. The resultant effect of the horizontal forces of the pore pressure is not significant and had been neglected. The overall calculation is in Table 8. An example of the calculation for block 13 is done.

- Inclination of the slip surface:
  $\alpha_{13} = 27.7192°$
- Inclination of the ground water table:
  $\alpha_{w,13} = 25.0169°$
- Height of the ground water table:
  $h_{13} = 4.2369\ m$
- Calculation of the reduced height of the ground water table:
  $h_{r,13} = h_{13} \cdot \cos(\alpha_{w,13})^2 = 4.2369 \cdot \cos(25.0169)^2 = 3.479\, m$
- Calculation of the pore pressure:
  $u_{13} = \gamma_w \cdot h_{r,13} = 10.00 \cdot 3.479 = 34.790\, kPa$
- Calculation for all blocks:

Block	Inclination of the slip surface	Ground water table			Pore pressure
		Inclination of the ground water table	Height of the ground water table	Reduced height of the ground water table	
	α_i [°]	$\alpha_{w,i}$ [°]	h_i [m]	$h_{r,i}$ [m]	u_i [kPa]
1	-19.5956	0.0000	0.1880	0.188	1.880
2	-15.5860	0.0000	0.5048	0.505	5.050
3	-11.6525	25.0169	0.9803	0.805	8.050
4	-7.7741	25.0169	1.6180	1.329	13.290
5	-3.9314	25.0169	2.1871	1.796	17.960
6	0.1065	25.0169	2.6890	2.208	22.080

7	3.6119	25.0169	3.1242	2.565	25.650
8	7.5592	25.0169	3.4922	2.868	28.680
9	11.4351	25.0169	3.7917	3.114	31.140
10	15.3650	25.0169	4.0202	3.301	33.010
11	19.3709	25.0169	4.1744	3.428	34.280
12	23.4785	25.0169	4.2489	3.489	34.890
13	27.7192	25.0169	4.2369	3.479	34.790
14	32.1331	25.0169	4.1285	3.390	33.900
15	36.7741	25.0169	3.9099	3.211	32.110
16	41.7186	25.0169	3.5609	2.924	29.240
17	47.0841	25.0169	3.0504	2.505	25.050
18	53.0703	0.0000	2.0928	2.093	20.930
19	60.0828	0.0000	0.5872	0.587	5.870
20	69.3348	0.0000	0.0000	0.000	0.000

Table 8 Inclinations of the slip surfaces and pore pressures

Calculation of the sliding moment. The weight of the individual blocks including forces of the load act on the horizontal arm from the axis of the block to the centre of the circle slip surface (to the point O). The arms of the forces are calculated from the edge of the slip surface ($Z_{sp} = [x, z] = [8.00; 5.00]$). The overall calculation is shown in Table 9. An example of the calculation for block 13 is done.

- Calculation of the arm of the force:

$$r_{a,13} = X_{zsp} - X_O + \left(i \cdot b - \frac{b}{2} \right) = 8.0000 - 13.5729 + \left(13 \cdot 1.0 - \frac{1.0}{2} \right) = 6.972\ m$$

- Calculation of the sliding moment:

$$M_{a,13} = (W_{13} + f_{13}) \cdot r_{a,13} = (121.236 + 0.000) \cdot 6.972 = 845.257\ kNm/m$$

- Calculation for all blocks:

Block	Sliding moment		Block	Sliding moment	
	$r_{a,i}$ $[m]$	$M_{a,i}$ $[kNm/m]$		$r_{a,i}$ $[m]$	$M_{a,i}$ $[kNm/m]$
1	-5.028	-17.452	11	4.972	560.126
2	-4.028	-38.919	12	5.972	703.460
3	-3.028	-62.958	13	6.972	845.257
4	-2.028	-74.904	14	7.972	978.874
5	-1.028	-53.184	15	8.972	1096.172
6	-0.028	-1.826	16	9.972	1186.648
7	0.972	75.241	17	10.972	1235.645
8	1.972	174.088	18	11.972	1383.496
9	2.972	290.706	19	12.972	1116.708
10	3.972	420.885	20	13.972	646.275

Table 9 Sliding moments

- Resultant sliding moment:

$$M_a = \sum_{i=1}^{20} M_{a,i} = 10464.338\ kNm/m$$

Result from the GEO5 – Slope Stability program: $M_a = 10447.88\ kNm/m$

- Resultant active force:

$$F_a = \frac{\sum_{i=1}^{20} M_{a,i}}{R} = \frac{10464.338}{15.00} = 697.623\ kN/m$$

Result from the GEO5 – Slope Stability program: $F_a = 696.53\ kN/m$

Calculation of the resisting moment. The calculation of the resisting moments is iterative because the calculation of the resisting moments according to Bishop's method depends on the safety factor FS. In the 1st iteration the safety factor $FS = 1.500$ is considered. Five iterations are done in the hand-made calculation. The overall calculation is shown in Table 10. An example of the calculation for block 13 is done.

- Calculation of the safety factor FS in the individual iterations:

$$FS = \frac{M_p}{M_a}$$

- Calculation of the resisting moment, $FS = 1.500$:

$$M_{p,13} = \frac{c \cdot b_{13} + (W_{13} + f_{13} - u_{13} \cdot b_{13}) \cdot \tan(\varphi)}{\cos(\alpha_{13}) + \frac{\tan(\varphi) \cdot \sin(\alpha_{13})}{FS}} \cdot R$$

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.500}} \cdot 15.00 = 935.258\ kNm/m$$

$\rightarrow FS = 1.546$ - result of the 1st iteration

- Calculation of the resisting moment, $FS = 1.546$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.546}} \cdot 15.00 = 939.492\ kNm/m$$

$\rightarrow FS = 1.553$ - result of the 2nd iteration

- Calculation of the resisting moment, $FS = 1.553$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.553}} \cdot 15.00 = 940.117\ kNm/m$$

$\rightarrow FS = 1.554$ - result of the 3rd iteration

- Calculation of the resisting moment, $FS = 1.554$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \dfrac{\tan(27.00) \cdot \sin(27.7192)}{1.554}} \cdot 15.00 = 940.206 \; kNm/m$$

$\rightarrow FS = 1.554$ - result of the 4th iteration

- Calculation of the resisting moment, $FS = 1.554$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \dfrac{\tan(27.00) \cdot \sin(27.7192)}{1.554}} \cdot 15.00 = 940.206 \; kNm/m$$

$\rightarrow FS = 1.554$ - result of the 5th iteration

- Calculation for all blocks:

Block	1st iteration		2nd iteration		3rd iteration		4th iteration		5th iteration	
	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS
1	395.044	1.546	393.434	1.553	393.198	1.554	393.165	1.554	393.165	1.554
2	401.680		400.433		400.250		400.224		400.224	
3	452.781		451.769		451.620		451.599		451.599	
4	524.644		523.886		523.775		523.759		523.759	
5	588.222		587.805		587.742		587.734		587.734	
6	644.339		644.351		644.353		644.353		644.353	
7	697.048		697.484		697.548		697.557		697.557	
8	743.745		744.700		744.841		744.861		744.861	
9	787.201		788.710		788.932		788.964		788.964	
10	827.660		829.768		830.079		830.123		830.123	
11	865.500		868.256		868.663		868.721		868.721	
12	901.264		904.725		905.236		905.309		905.309	
13	935.258		939.492		940.117		940.206		940.206	
14	967.766		972.856		973.608		973.715		973.715	
15	999.018		1005.073		1005.969		1006.097		1006.097	
16	1029.345		1036.514		1037.576		1037.727		1037.727	
17	1058.707		1067.203		1068.464		1068.643		1068.643	
18	1190.155		1201.280		1202.933		1203.168		1203.168	
19	1170.095		1183.162		1185.108		1185.385		1185.385	
20	996.701		1010.954		1013.084		1013.387		1013.387	
TOTAL	16176.173		16251.854		16263.096		16264.697		16264.697	

Table 10 Resisting moments and safety factors

- Resultant resisting moment in 5th iteration:

$$M_p = \sum_{i=1}^{20} M_{p,i} = 16264.697\ kNm/m$$

Result from the GEO5 – Slope Stability program: $M_p = 16280.28\ kNm/m$

- Resultant passive force:

$$F_p = \frac{\sum_{i=1}^{20} M_{p,i}}{R} = \frac{16264.697}{15.00} = 1084.313\ kN/m$$

Result from the GEO5 – Slope Stability program: $F_p = 1085.35\ kN/m$

- Calculation of the safety factor in 5th iteration:

$$FS = \frac{M_p}{M_a} = \frac{16264.697}{10464.338} = 1.554$$, SATISFACTORY

Result from the GEO5 – Slope Stability program: $FS = 1.56$**, SATISFACTORY**

Verification of the Stability of Anchored Slope

In Figure 4, an example of anchored slope in 2nd stage is shown. The anchor force is $F_A = 200.00\ kN$ and the spacing is $b_A = 2.00\ m$. The position of the anchor head is $H_{anchor} = [x, z] = [16.00; 9.00]$.

Calculation of the sliding moment. The anchor acts as a passive element, which means that active moments will be the same as in the 1st stage.

- Resultant sliding moment:

$$M_a = \sum_{i=1}^{20} M_{a,i} = 10464.338\ kNm/m$$

Result from the GEO5 – Slope Stability program: $M_a = 10447.88\ kNm/m$

- Resultant active force:

$$F_a = \frac{\sum_{i=1}^{20} M_{a,i}}{R} = \frac{10464.338}{15.00} = 697.623\ kN/m$$

Result from the GEO5 – Slope Stability program: $F_a = 696.53\ kN/m$

Calculation of the resisting moment. The anchor force enters the calculation of the resisting moments. The calculation of the resisting moments is iterative because the calculation of the resisting moments using the Bishop's method depends on the safety factor FS. In the 1st iteration the safety factor is $FS = 1.500$. Five iterations are done in the hand-made calculation. The overall calculation is shown in Table 11. An example of the calculation for block 13 is done.

- Anchor force at 1 m:

$$F_A^{'} = \frac{F_A}{b_A} = \frac{200.00}{2.00} = 100.00\ kN/m$$

- Calculation of the arm of the anchor force:

$$r_A = Z_O - Z_{anchor} = 18.944 - 9.000 = 9.944\ m$$

- Resisting moment of the anchor:

$$M_{p,A} = F_A^{'} \cdot r_A = 100.00 \cdot 9.944 = 994.400\ kNm/m$$

- Calculation of the safety factor FS in the individual iterations:

$$FS = \frac{M_p}{M_a}$$

- Calculation of the resisting moment, $FS = 1.500$:

$$M_{p,13} = \frac{c \cdot b_{13} + (W_{13} + f_{13} - u_{13} \cdot b_{13}) \cdot \tan(\varphi)}{\cos(\alpha_{13}) + \frac{\tan(\varphi) \cdot \sin(\alpha_{13})}{FS}} \cdot R$$

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1{,}00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.500}} \cdot 15.00 = 935.258\ kNm/m$$

$\rightarrow FS = 1.641$ - result of the 1st iteration

- Calculation of the resisting moment, $FS = 1.641$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.641}} \cdot 15.00 = 947.589\ kNm/m$$

$\rightarrow FS = 1.662$ - result of the 2nd iteration

- Calculation of the resisting moment, $FS = 1.662$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.662}} \cdot 15.00 = 949.272\ kNm/m$$

$\rightarrow FS = 1.665$ - result of the 3rd iteration

- Calculation of the resisting moment, $FS = 1.665$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.665}} \cdot 15.00 = 949.509 \ kNm/m$$

$\rightarrow FS = 1.665$ - result of the 4th iteration

- Calculation of the resisting moment, $FS = 1.665$:

$$M_{p,13} = \frac{21.00 \cdot 1.00 + (121.236 + 0.00 - 34.790 \cdot 1.00) \cdot \tan(27.00)}{\cos(27.7192) + \frac{\tan(27.00) \cdot \sin(27.7192)}{1.665}} \cdot 15.00 = 949.509 \ kNm/m$$

$\rightarrow FS = 1.665$ - result of the 5th iteration

- Calculation for all blocks:

Block	1st iteration		2nd iteration		3rd iteration		4th iteration		5th iteration	
	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS	$M_{p,i}$ $[kNm/m]$	FS
1	395.044		390.429		389.817		389.731		389.731	
2	401.680		398.100		397.623		397.556		397.556	
3	452.781		449.870		449.481		449.427		449.427	
4	524.644		522.461		522.169		522.128		522.128	
5	588.222		587.016		586.855		586.832		586.832	
6	644.339		644.374		644.378		644.379		644.379	
7	697.048		698.308		698.478		698.502		698.502	
8	743.745		746.511		746.885		746.937		746.937	
9	787.201		791.574		792.165		792.249		792.249	
10	827.660		833.776		834.605		834.722		834.722	
11	865.500	1.641	873.507	1.662	874.595	1.665	874.748	1.665	874.748	1.665
12	901.264		911.332		912.703		912.896		912.896	
13	935.258		947.589		949.272		949.509		949.509	
14	967.766		982.612		984.642		984.929		984.929	
15	999.018		1016.706		1019.131		1019.474		1019.474	
16	1029.345		1050.323		1053.208		1053.616		1053.616	
17	1058.707		1083.621		1087.059		1087.545		1087.545	
18	1190.155		1222.859		1227.393		1228.034		1228.034	
19	1170.095		1208.644		1214.020		1214.781		1214.781	
20	996.701		1039.003		1044.965		1045.810		1045.810	
Anchor	994.400		994.400		994.400		994.400		994.400	
TOTAL	17170.573		17393.015		17423.844		17428.205		17428.205	

Table 11 Resisting moments and safety factors

- Resultant resisting moment in 5th iteration:

$$M_p = \sum_{i=1}^{20} M_{p,i} + M_{p,A} = 16433.805 + 994.400 = 17428.205\ kNm/m$$

Result from the GEO5 – Slope Stability program: $M_p = 17442.70\ kNm/m$

- Resultant passive force:

$$F_p = \frac{\sum_{i=1}^{20} M_{p,i} + M_{p,A}}{R} = \frac{16433.805 + 994.400}{15.00} = 1161.880\ kN/m$$

Result from the GEO5 – Slope Stability program: $F_p = 1162.85\ kN/m$

- Calculation of the safety factor in 5th iteration:

$$FS = \frac{M_p}{M_a} = \frac{17428.205}{10464.338} = 1.665$$, SATISFACTORY

Result from the GEO5 – Slope Stability program: $FS = 1.67$ **, SATISFACTORY**