Numerical modelling of the Balatonaliga slope (Hungary)

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Abstract:

An earthquake can cause significant damage to an high bank with low factor of safety, even if the earthquake is considered small. Numerical simulation of the high bank was carried out in Plaxis.

The first part of the work focuses on the geology and earthquake conditions in the area. This is followed by a presentation of the field and laboratory investigations carried out at the study area and the soil parameter limits derived from these.

Then the numerical modelling with Plaxis 2D software. Sensitivity analysis is used to calibrate the soil parameters for the persistent situation. Afterwards, proposals are presented to reinforce the high bank to resist the ground acceleration value corresponding to the earthquake value for the area.

Keywords: high bank, earthquake, pseudo-static analysis, numerical modelling, Plaxis, reinforcement

1. INTRODUCTION

The High Bank is located in Hungary, on the north-eastern shore of Lake Balaton. I chose the High Coast as the subject of my dissertation because I have worked in the area before. I examined the earthquake safety of 10 cross-sections of the high coast. I was interested in the complexity of the high coast and also in earthquake science, which is why I chose this topic.

The high bank was naturally formed relatively high, vertical wall (105-108mBf base – 147-148 mBf top) close to a lake or sea. This high bank is formulated from lake sedimentation at the Miocene epoch. The behaviour of a geological structure like this depends on its soil parameters and the geometry.

2. EARTHQUAKE

Earthquakes are generated by tectonic movements. When two or more tectonic plates converge, drift apart or slide part on each other, stress stored in the rocks can be released and an earthquake event can occur. [1]

2.1 PAST EARTHQUAKE

Earthquake events with Richter scale magnitudes of 4.9 and 2.8 Richter scale earthquakes occurred in the vicinity of the study area in the Berhida municipality in 1985 and 2009. This area is located approximately ~14km NE of the study area. The area is typically subject to earthquake events of magnitude 4.5 to 5 every 10 years. (Figure 1) [2] [3]

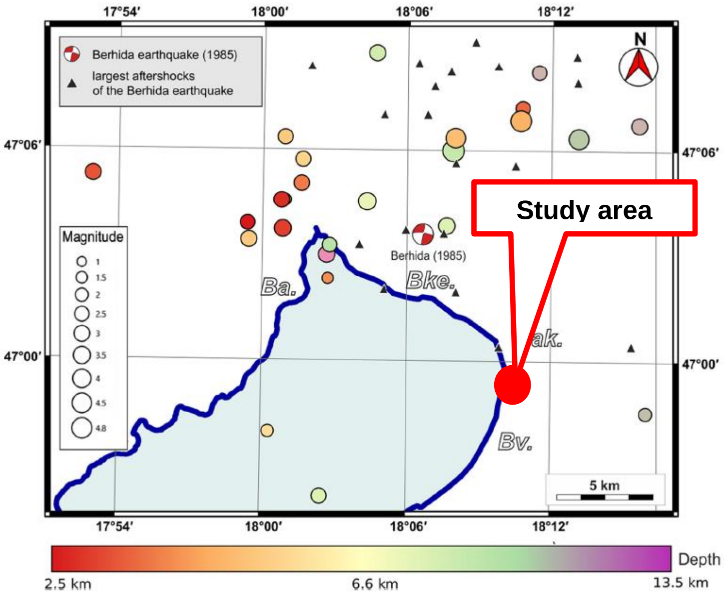

Figure 1 Seismicity of the north-eastern part of Lake Balaton, Hungary **[4, p. 6]**

2.2 EUROCODE 8

According to the Hungarian national annex to EUROCODE 8, the horizontal soil acceleration can be determined by multiplying the bedrock acceleration and the soil factor to obtain a site-specific value. [5]

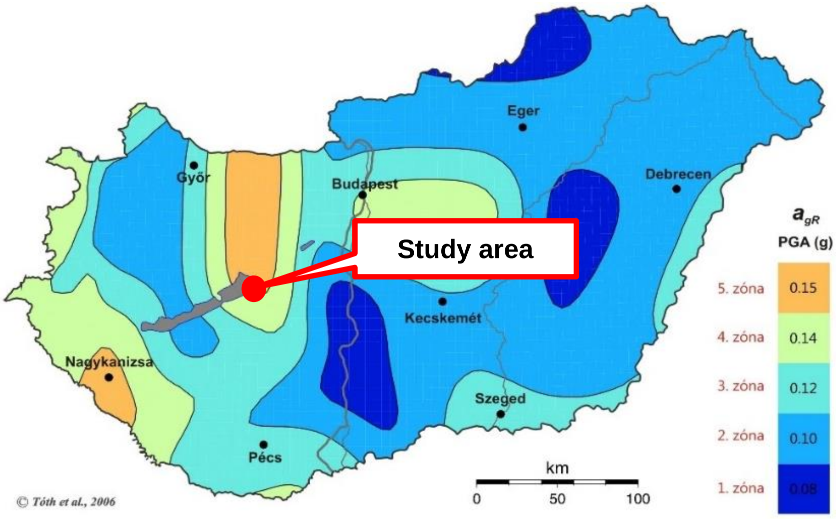

Figure 2 Seismic zone map of Hungary **[6]**

As shown in Figure 2, a_g^R=0,15 in the vicinity of the site. According to laboratory tests, the soil was classified (S) as type C, therefore the applied soil factor: 1,5. There are residential houses ~30 meters from the edge of the top of the high bank, that is why a value of 1.0 has been taken as the importance factor (γ_I). According to the Eurocode 8, topographic amplification factor (S_T) should use if the angle of the slope is higher than 15° coefficient variation of 1,2 should be taken into account. To calculate the pseudo static acceleration according to the Eurocode 8 recommendation, the above values must be multiplied by 0.5.

$$ag = 0{,}5 * agR * \gamma I * S * S_T = 0{,}5 * 0{,}15g * 1 * 1{,}5 * 1{,}2 = 0{,}135 * g = 1{,}324 m/s2$$

3. GEOLOGICAL SETTING

The study area is located on the north-eastern shore of Lake Balaton in Hungary. The high bank was formed from the Miocene Pannonian Lake. The material building up the shoreline below the Quaternary formations are the Upper and Lower Pannonian formations of the Miocene Pannonian Elevation. (Figure 3)

Figure 3 Lake Balaton. The study area located at the most north-eastern point of Lake Balaton (marker) [7]

In addition, the following Quaternary formations are found in the area: Holocene lake sediment ($_{l}\mathbf{h}$), upper Pleistocene loess ($_{e}\mathbf{Qp_3}^{l}$), upper Pleistocene-Holocene clastic aleurite ($_{d}\mathbf{Qp_3\text{-}h}^{yal}$), lake shore made ground ($_{a}\mathbf{Qh}^{f}\mathbf{_2}$), upper Pannonian Tihany Formation ($^{t}\mathbf{Pa_2}$), Nagyvárzsonyian limestone formation($^{nv}\mathbf{Pa_2}$) and Fluvial proluvial sediment ($_{fp}\mathbf{Qp_{1\text{-}2}}$). [8]

During the site visit and borehole drilling, stratified water was revealed in the high bank. Aquifer modelling was based on the water table encountered in the boreholes. Three aquifers were modelled.

4. FIELD AND LABORATORY TESTS

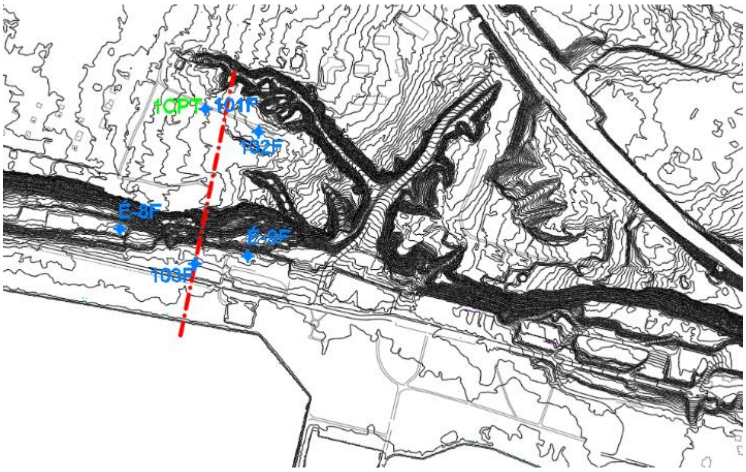

Figure 4 Boreholes and CPT explorations on the study area

There were 5 boreholes and 1 CPT field survey in the area, the locations of which are shown in Figure 4. The results of the field studies were provided by EFERTE Ltd. [9]

The red dashed line is the selected test cross-section.

Samples from boreholes, triaxial examination are later used for triaxial CD and UU examinations, sieve analysis, Atterberg limits analysis, undrained direct shear and material density analysis.

A CPT field study was also carried out in the area, the results of which were also used in the determination of soil parameters.

Based on the combined results of laboratory, geological and deep boreholes, three geotechnical zones (GZ) were established in the study cross-section. Figure 5

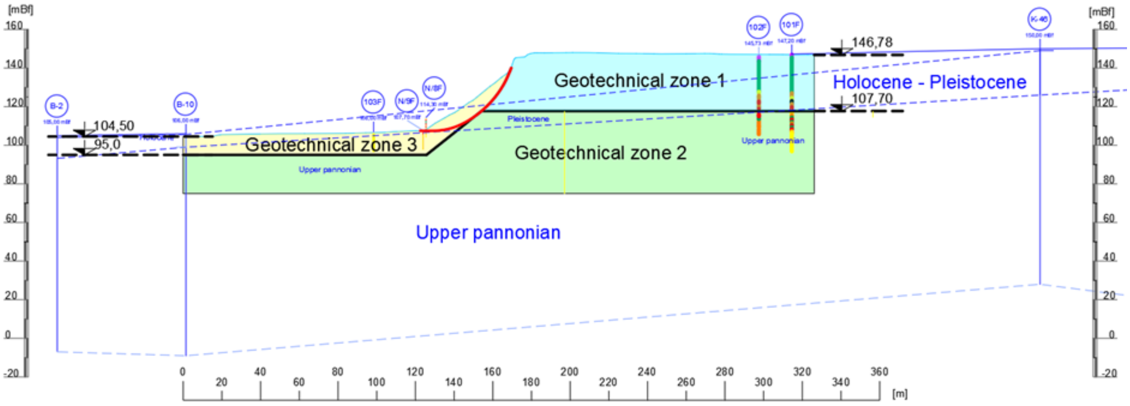

Figure 5 Geotechnical zones

Correlation procedures from the Atterberg limit test and CPT tests were also used to determine the soil parameters for the angle of shear resistance and the E50 value.

The values obtained from the laboratory, field tests and correlation procedures were plotted in graphs, as shown in Figure 6. By plotting the results in this way, it is easy to select the parameter limits, which are indicated by the vertical grey lines: also, medium, and upper limits.

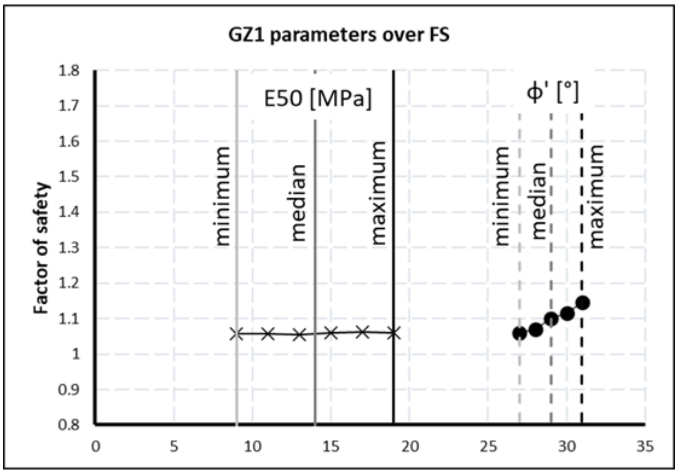

Figure 6 E50 and φ' values regarding Geotechnical zone 1

The same plots were made for the angle of shearing resistance, apparent cohesion, and undrained shear strength parameters in GZ1 and GZ2.

A summary of the parameter limits is shown in Table 1.

Table 1 The range of the input parameters for GZ1 and GZ2

	GZ1			GZ2		
	min	mean	max	min	mean	max
E' [kPa]	9	14	19	15	25	35
Cref [kPa]	40	45	50	40	45	50
phi' [°]	27	29	31	27	28.5	30
Su [kPa]	200	250	300	300	375	450
Poisson ratio [v]	0.3	0.4	0.5	0.3	0.4	0.5

5. NUMERICAL MODEL

Numerical modelling was carried out using the Plaxis 2D finite element analysis program. The cross section was generated from the geodetic terrain surface using AutoCAD Civil 3D.

The finite element mesh was created using Plaxis tool adopting fine meshing option. A total of 12745 elements were created

For groundwater conditions, the global groundwater table was taken to be the water table of Lake Balaton. Aquifers in the high bank were also modelled in the pseudo static and reinforcement test phases. In the case of aquifers, the undrained behaviour is more important, because in case of an earthquake, even the more granular soils cannot drain pore water and may exhibit undrained behaviour.

For numerical modelling, both drained and undrained cases have been considered.

For numerical modelling, all 5 different phases were used in the Plaxis 2D program. The first one is the Initial Phase, which is a gravity load on the high bank, required to be run for models with non-horizontal geometry. This is followed by the "null" phase, which is a plastic test with no additional load. It is recommended to run it after the gravity test. This was followed by the safety factor analysis, which tests the stability of the model in iterative steps. Starting from the Initial phase, the pseudo static test is the pseudo static analysis, where the horizontal and vertical ground acceleration values are applied to the high bank. Finally, this is followed by a safety factor analysis for the pseudo static test. [10]

6. SENSITIVITY ANALYSIS

The first step in the program was to set the parameters for GZ1 and GZ2. At this point, the GZ3 layer was switched off. The aim was to get back the state of the high bank before the slip, when the value of the safety factor should be close to 1. After many iterations of calculations, the various soil parameters were modified to within the previously defined range of values. The resulting values are shown in Table 1 (Figure 7).

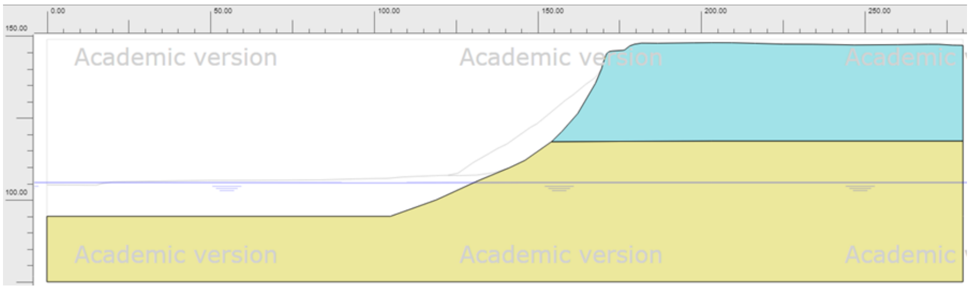

Figure 7 Numerical model for GZ1 and GZ2 iteration

From the iteration process, it was found that changing the secant modulus and the undrained shear strength has insignificant effect on the value of FS, but it should at least assume a certain minimum value. A linear relationship was found for Φ' and cohesion with the value of the safety factor.

GZ3 was then calibrated using the same method. The values obtained as a result of the iteration process are shown in Table 2. (Figure 8)

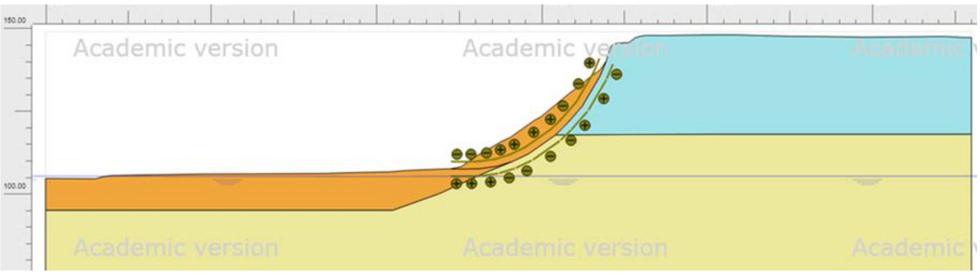

Figure 8 The model with the activated GZ3

Table 2 Applied soil parameters

	GZ1	GZ2	GZ3
E50 [kPa]	15000	25000	12000
phi' [°]	27	28	27
cohesion [kPa]	45	45	15
su [kPa]	-	300	5

7. PSEUDO STATIC ANALYSIS

In the pseudo static study, the earthquake simulation is performed using the Plaxis 2D program, using the previously presented ag value. To get an idea of the horizontal ground acceleration value that the tested cross-section can withstand, progressively increasing acceleration values were applied to the model, from which a factor of safety analysis was then performed. The results are shown in Figure 9.

For this test, interface elements were switched on. They were placed where the potential slip plane could be formed. (Figure 8)

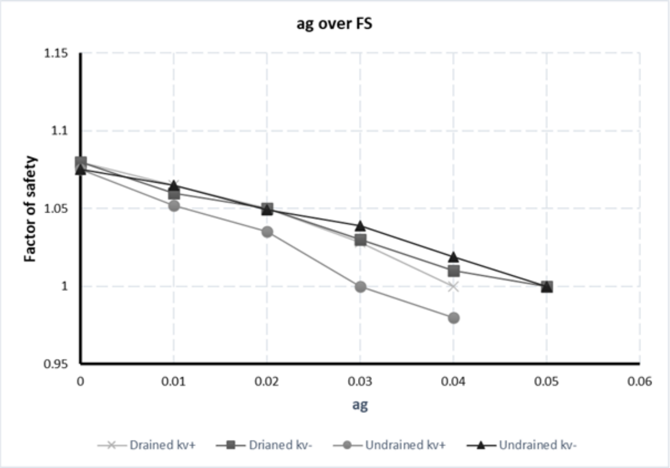

Figure 9 Ground accelerations over factor of safety

Figure 9 shows that the cross-section, with the specified soil parameters and geometry, can support ~0.03-0.04*g. However, a value of 0.135*g would be required. The pseudo static test was also run with activated aquifers. The results are almost identical to those shown in the Figure 9. For the high bank to withstand the earthquake magnitude for the study area, reinforcement is required. The cases examined are shown in Table 3

Table 3 calculated cases

	Case 1	Case 2	Case 3	Case 4
GZ1	Drained	Drained	Drained	Drained
GZ2	Drained	Undrained	Drained	Undrained
GZ3	Drained	Undrained	Drained	Undrained
Kh [g]	0.0135	0.0135	0.0135	0.0135
Kv [g]	0.00675	0.00675	-0.00675	-0.00675

8. REINFORCEMENT

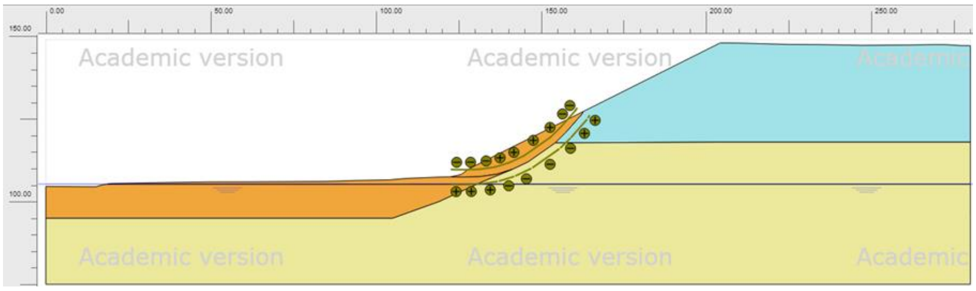

Figure 10 Cutting with 1:2 slope ratio

To strengthen the high bank, two methods have been used: cutting: 1:2 and 1:3 slope ratio, and soil nailing. (Figure 10)

On Figure 10 can see the cutting in case of 1:2 slope ratio. In this case 341 m^2 earth work needed.

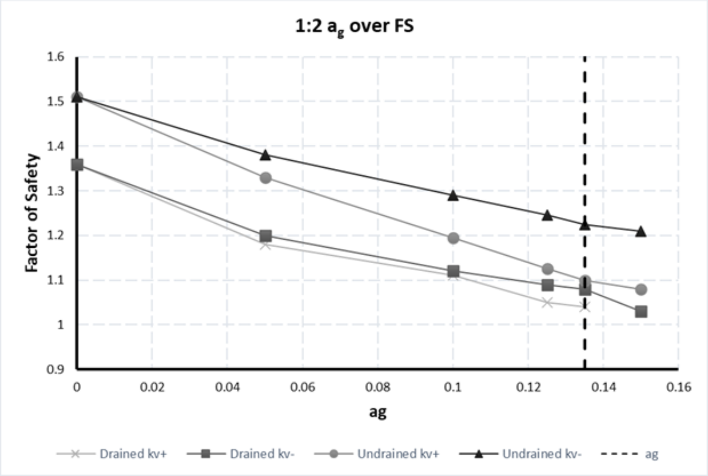

Figure 11 Horizontal acceleration values over factor of safety regarding 1:2 cut

Figure 11 represents the horizontal accelerations of FS value. To determine the sufficient cut iteration process had done.

In the case of activated aquifers, the same cutting is seems appropriate (Figure 12)

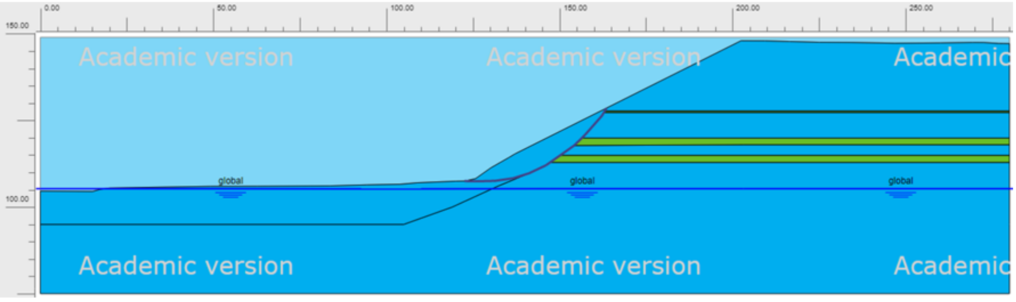

Figure 12 Cutting with 1:2 slope ratio with aquifers (green bands)

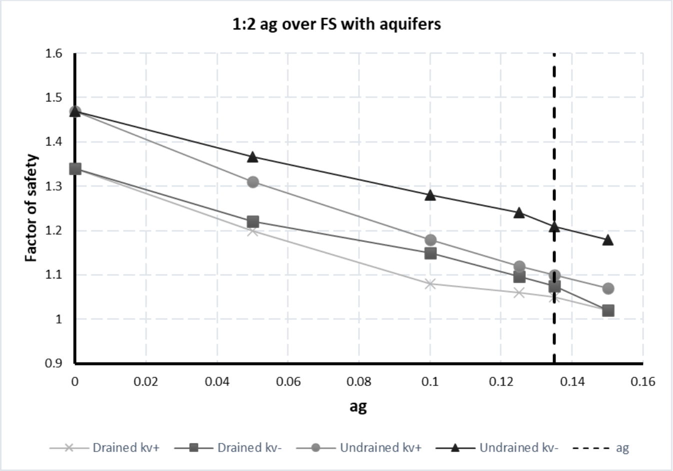

Figure 13

The 1:3 cut will require 670 m2 of earthworks to ensure the stability of the high bank. When aquifers are used, tension cracks are formed in the top aquifer at the surface of the slope. It usually because that the angle of shearing resistance is higher than the slope angle. Which is similar to the infinite slope failure. For this reason, a 1:3 slope ratio was found to be inappropriate. Plaxis is therefore unable to perform the calculation.

The soil nailing process has been modelled with Geo5 and Plaxis. Geo 5 uses LEM, Plaxis uses FEA. The potential circle sliders are different, mainly due to the difference between the two methods. (Figure 14, Figure 15)

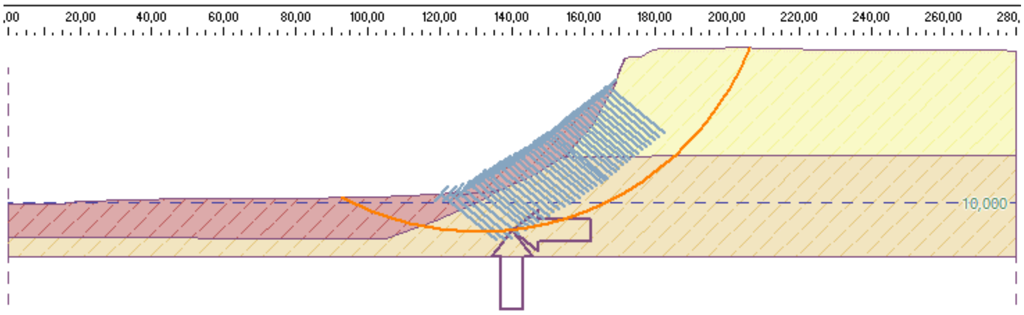

Figure 14 Reinforcement with nails in Geo 5

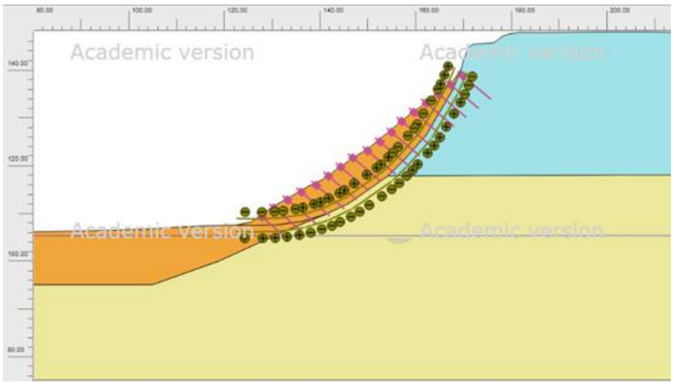

Figure 15 Reinforcement with nails in Plaxis

The soil nailing process was pre-iterated with Geo5 slope stability and later checked in Plaxis. (Figure 15)

Applied nail parameters: 17pcs, 9 meters long soil nail. With a horizontal spacing of 1m and a vertical spacing of 1,9m. Diameter of nails 32mm, angle with horizontal: 40°, and have E= 210kPa, γ= 60kPa.

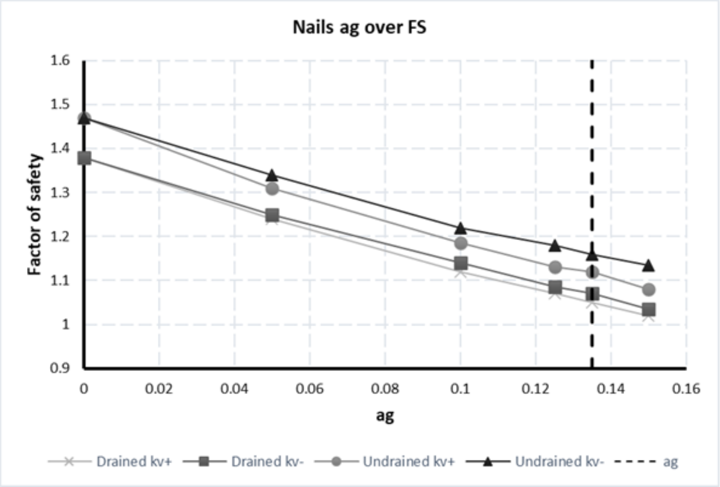

Figure 16 Horizontal acceleration values over factor of safety regarding nailing

Figure 16 represents the horizontal accelerations of FS value. To determine the sufficient nailing iteration process had done.

The modelling of soil nailing with aquifers has shown that longer and denser nailing is needed to keep the high bank stable. Applied nail parameters: 21pcs, 9 meters long, horizontal spacing: 1m, vertical spacing: 1,5 meters. Diameter of nails 32mm, angle with horizontal: 40°, and have E= 210kPa, γ= 60kPa.

9. CONCLUSIONS

The values of the parameter range table from the laboratory and field tests were refined, aiming at search the parameter for FS=1 from above. Thus, the parameters GZ1 and GZ2 were fitted. In the next step, the previously calibrated parameters were used to calibrate GZ3. Here the aim was to approximate a value around FS=~1.1.

The calibrated parameters were used to model the current state of the high bank with the defined geotechnical zones, the calibrated parameters, and the geometry to determine the horizontal soil acceleration value that the high bank can withstand. The results showed that it is significantly less than required and therefore a wall of the high bank reinforcement is needed. The results were almost identical for the aquifers that were turned on. There are 3 different recommendations for reinforcement: 1:2 and 1:3 slope ratio cutting and soil nailing.

For a 1:2 cutting with the aquifers turned on, the same slope cut-off is found to be appropriate. In the case of the 1:3 slope ratio, with the activated aquifers, the Plaxis calculation did not run, as a tension crack formed at the top aquifer layer boundary, even if all the slope debris were cut off.

The soil nailing was first modelled with Geo5, using the Limit Equilibrium Method, with length: 20m, inclination: 40°.In Plaxis, the 17pcs, 9 meters, with 40° inclination nails was needed, in the case of aquifers 21 nails.

In Geo5 and Plaxis modelling, there is a significant difference in the length of the nails. This may be because in Plaxis, interface elements were activated at the falling debris with a multiplication factor of 0.67, so that, in Plaxis, the failure occurs there without reinforcement. At Geo 5, however, it is at it has a different shape. This is due to the shorter nails being able to hold the soil mass stably. This example illustrates the difference between LEM and FEA modelling.

The 1:2 and 1:3 slope cuts shown, the 1:2 ratio cut, or the soil nailing seems the appropriate solution. A The 1:3 cut is not good because it would mean too much excavation. Soil nailing also seems to be an applicable method, as it does not require very long nails, nor too many. However, trees and bushes on slope of the high bank and a terrain slope of 30-32° make it difficult to implement. Therefore, a cut-off ratio of 1:2 seems appropriate.

10. REFERENCES

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