Numerical analysis of an upstream tailings dam

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ABSTRACT
This paper presents a case study of how the finite element method can be utilized to analyze stability of upstream tailings dams. Upstream tailings dams are usually raised gradually and the increased load normally influences the stability in an unfavorable way; the load generates excess pore water pressures and reduced stability. In this study, an upstream tailings dam in Northern Sweden was numerically simulated with the finite element software PLAXIS 2D in order to assess the stability of the dam. Upstream tailings dams are sensitive to high raising rates since initiated excess pore water pressures might not have time to dissipate. Stability analysis of a tailings dam is an application that is very suitable to carry out using finite element software; once a finite element model of the complex geometry of a dam has been established, it is easy to stepwise add new soil volumes, associated with each new raising, to the model.

In this case study, it was found that strengthening actions were needed in order to maintain a stable structure. Rockfill berms were gradually added on the downstream slope of the model to obtain a factor of safety above a recommended value. The volumes of rockfill needed for the berms were minimized by numerical optimization to reduce costs. The stability between the years 2024 and 2034 was analyzed; with an annual deposition cycle.

The performed numerical study resulted in a future plan for placement of rockfill berms to establish sufficient stability of the tailings dam. It was found that the volume of rockfill in the berms needed, varied during the years studied. Numerical modeling, as presented in this paper, is a useful tool for the dam owner to plan and design for future raisings of a tailings dam.

Keywords: Numerical simulation, tailings dam, stability, excess pore water pressure

1 INTRODUCTION

Waste material from mining facilities has to be taken care of in economic, environmental and safety aspects. This waste material is usually deposited in large impoundments surrounded by embankment dams i.e. tailings dams. The tailings dams have to be raised continuously to maintain storage for new generated tailings material. Tailings dams can be raised mainly by three different methods; upstream construction, downstream construction or centerline construction (Vick, 1990).

The aim of this paper is to show how the finite element method, in this case with the software PLAXIS 2D (Brinkgreve et al., 2014), can be utilized as a tool for dam safety analysis. A tailings dam mainly built by the upstream method is investigated between the years 2024 and 2034 to assess its future stability. The tailings dam is raised annually and its stability is ensured by adding rockfill berms on the downstream slope of the dam. The locations of the berms are optimized with the aim to minimize the total volume of rockfill. If sufficient stability of the studied dam in the existing impoundment can be achieved in the future, the owner does not need to find other deposition options for the generated tailings.

The tailings dam investigated in this paper is located in Aitik in Northern Sweden and has previously been examined by Ormann et al. (2013), Ormann et al. (2011) and Knutsson et al. (2015); where numerical simulations were utilized. Both in Ormann et al. (2013) and Ormann et al. (2011) the time period studied is not the same as in the present study, nor the constitutive model for the tailings material. The study conducted by Knutsson et al. (2015) contains deformation analyses and estimations of excess pore water pressures between the years 2014 and 2024.

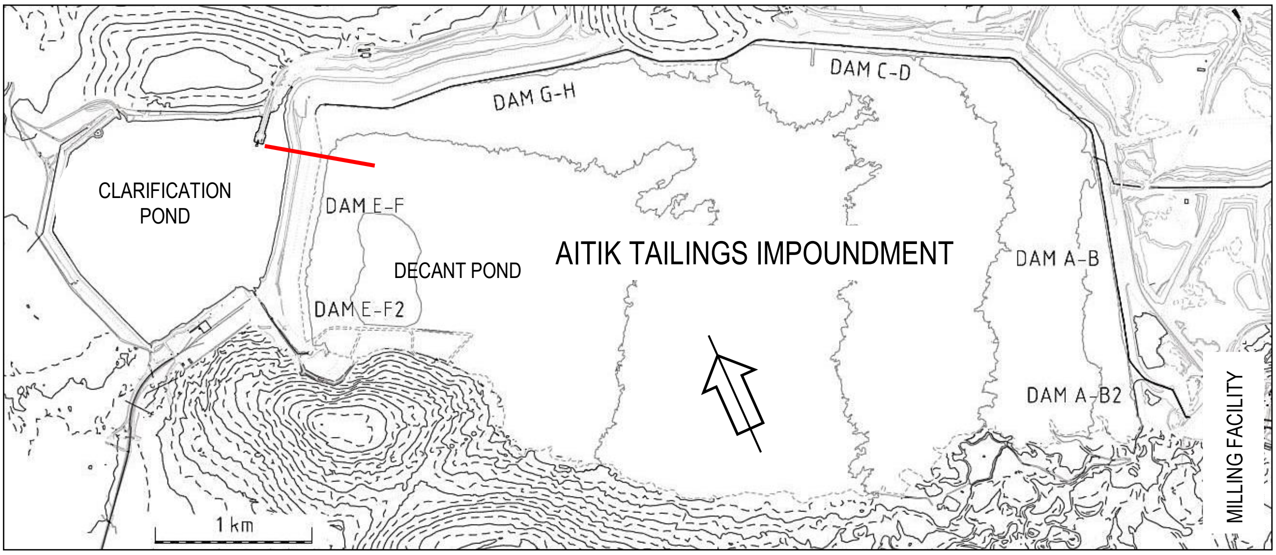

Figure 1 The studied tailings dam E-F is located between the tailings impoundment and the clarification pond. The red line shows the examined cross section of the tailings dam. (Knutsson, 2014)

The results were used to assess the dam stability. By utilizing the factors of safety, *FoS*, alert values were estimated for monitoring programs. Studies regarding tailings material in the Aitik impoundment were carried out by Bjelkevik (2005) and Bhanbhro (2014) where behaviors and material properties of the tailings were investigated.

2 AITIK TAILINGS DAM

The tailings dam studied is located in Aitik, Northern Sweden. The Aitik mine is an open pit copper mine that has been operational since 1968 and is owned by Boliden Mineral AB. The ore contains less than one percent of copper and with an annual production of 39 million tonnes of ore (year 2014) huge amounts of waste material are generated. The impoundment area, where the tailings material is deposited, is approximately 13 km^2 and is surrounded by tailings dams and by natural heights. The tailings dam E-F is chosen for the numerical analysis in this study and is located between the tailings impoundment and the clarification pond, see Figure 1. The most critical failure scenario occurs when a failure of tailings dam E-F results in a failure of the embankment dam surrounding the clarification pond. A failure like this might cause environmental damages downstream of the impoundment facilities. (Sweco Infrastructure AB and TCS AB, 2012)

The tailings material is mixed with water from the processing plant to produce a slurry. Thereafter, the slurry is distributed through pipes and deposited in the impoundment. Between approximately the period 15th of October and 30th of April the tailings material is deposited from a single discharge point from tailings dam A-B, close to the milling facility, see Figure 1 (Sweco Infrastructure AB and TCS AB, 2012). This method is used to prevent freezing in the pipes. Between approximately the period 1st of May and 14th of October the spigot method (Blight, 2010) is used and the tailings are distributed through spigots placed around the impoundment, see Figure 1. The spigot method creates segregation in the tailings material; coarser particles are settled close to the dam structure and finer particles further away. This phenomenon with coarser and finer particles separated, creates good foundation conditions for future dike constructions. The coarser particles contribute to a denser foundation which is required by the upstream method. The dissipation of excess pore water pressures corresponds to the consolidation process where coarser grained soil have higher hydraulic conductivity and allow the phreatic line to disperse faster than finer grained soil. The area between the dam structure and the decant pond is called beach and is required to

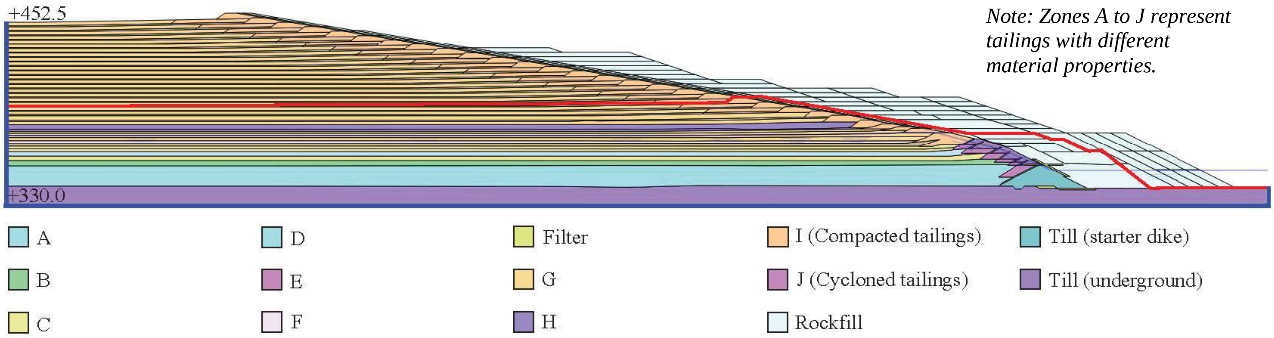

Figure 2 Material zones in the tailings dam. The red lines show the size of the dam year 2015 and the blue lines show the outer boundaries. The whole geometry is presented for year 2034.

make the phreatic level decrease before reaching the downstream slope of the dam. (Lottermoser, 2010) The beach at tailings dam E-F is between 100 and 200 meters wide. (Sweco Infrastructure AB and TCS AB, 2012)

3 FINITE ELEMENT MODEL

To increase impoundment storage for generated tailings, tailings dams have to be raised continuously with sufficient stability. According to Swedish recommendations, the stability of tailings dams has to be sufficient for a very long time; i.e. 1000 years (Bjelkevik, 2005; Svensk Energi AB/SveMin, 2012). Svensk Energi AB/SveMin (2012) recommends factors of safety, *FoS*, for tailings dams to be above 1.5 during normal operation conditions.

Plane strain conditions were applied in the finite element model since the dam was considered to be a long structure i.e. the length of the dam is much larger than the width of the dam; no deformations along the longitudinal direction were expected.

By simulating future raisings at the tailings dam between the years 2024 and 2034 in the finite element software PLAXIS 2D, the dam stability was assessed. If the dam stability in the simulations results in *FoS* values below the recommended value, strengthening actions have to be implemented. In this numerical analysis, rockfill berms were placed on the downstream slope of the dam to increase the dam stability.

Rockfill berms were assumed to be constructed on the downstream slope of the tailings dam between the period 15th of October and 30th of April, to increase the dam stability during the following dike construction. An optimization technique, where the volume of rockfill was minimized to fulfill the recommended stability, was utilized in the simulations. The basic idea with the technique was to place as small volumes of rockfill as possible on the downstream slope of the dam to obtain *FoS* values above the recommended value. The optimization technique used in this study was basically the same technique as used by Knutsson et al. (2015) and Ormann et al. (2013). In this paper and the paper by Knutsson et al. (2015) smaller rockfill berms were placed on several different places on the downstream slope, whilst Ormann et al. (2013) placed the whole volume of rockfill at only one additional suitable position on the downstream slope of the dam. The most suitable positions for the rockfill berms were found by trying various locations and different volumes. The procedure was repeated until a *FoS* above 1.5 was obtained for a reasonable small total volume of rockfill.

3.1 Geometry

The geometry of the dam cross section was provided by the dam owner Boliden Mineral AB. The geometry was extended with future dike raisings with the same layout as the dikes constructed today (year 2015), see Figure 2.

The width of the geometry was chosen sufficiently large to obtain realistic numerical results. The geometry was assumed to be closed for water flow in the left and the right

Table 1 Values of material properties for tailings in the dam structure in Figure 2 (Knutsson, 2014; Pousette, 2007; Bhanbhro, 2014). The material properties are defined in e.g. Brinkgreve et al. (2014).

	Unit	A	B	C	D	E	F	G	H	I	J
E_{50}^{ref}	kPa	7500	7500	4200	4000	3800	3800	2700	3700	3800	3800
E_{oed}^{ref}	kPa	8200	8200	3000	4200	5200	5200	2600	4800	5000	5000
E_{ur}^{ref}	kPa	48000	48000	20000	20000	20000	20000	17000	20000	17000	17000
m	-	0.5	0.5	0.6	0.5	0.7	0.7	0.5	0.9	0.6	0.6
p_{ref}	kPa	250	250	100	100	100	100	100	100	100	100
ν'_{ur}	-	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
c'_{ref}	kPa	15	15	13.7	25	14	21	4	15	10	10
ϕ'	°	17.5	17.5	26.7	16.3	17	14	19.4	16.9	26	26
ψ'	°	0	0	0	0	0	0	0	0	0	0
R_f	-	0.48	0.48	0.6	0.58	0.68	0.68	0.8	0.75	0.9	0.9
γ_{unsat}	kN/m^3	14.3	14.3	15.45	16.2	15.7	15.7	12.3	14.9	16	16
γ_{sat}	kN/m^3	19.3	19.3	20	20.5	20.1	20.1	18	19.5	19	19
e_{init}	-	1.0	1.0	0.83	0.75	0.81	0.81	1.3	0.9	0.5	0.5
k_x	m/days	0.00864	0.04752	0.0864	0.04752	0.04752	0.04752	0.0864	0.04752	0.4752	0.0864
k_y	m/days	8.64E-4	4.752E-3	0.00864	4.752E-3	4.752E-3	4.752E-3	0.00864	4.752E-3	0.04752	0.00864

vertical outer boundaries of the model, see Figure 2. The lower horizontal outer boundary was also assumed to be closed. Both horizontal and vertical deformations were modeled to not occur in the bottom boundary and for the left and right outer boundaries only vertical deformations were allowed.

The foundation for tailings dam E-F as well as the starter dike consist of till, see Figure 2. The first six dike raisings, counted from the starter dike, were also constructed of till. The subsequent dike raisings were constructed of compacted tailings. All dike constructions were equipped with filters and rockfill on the downstream slope to protect the slope from surface erosion. The tailings were disposed and depending on the milling process of the tailings, the material properties vary over the years. The rockfill berms were constructed during the winter, due to less work activity at the impoundment that time compared to summer periods. Furthermore, rockfill materials are less sensitive to freezing and thawing than materials with lower hydraulic conductivity.

3.2 Material properties

The geometry of the tailings dam studied was divided into different subareas to represent different soil layers, see Figure 2. The subareas have various sizes and different material properties. The values of the material parameters in Table 1 and Table 2 correspond to the letters and names shown in Figure 2.

All values of the material properties for the tailings in the impoundment came from laboratory tests presented by Pousette (2007). The constitutive model *Hardening Soil* (Brinkgreve et al., 2014) was chosen for the tailings material, since parameter values were available. Values of material properties for the constitutive model were evaluated by Pousette (2007), Knutsson (2014) and Bhanbhro (2014). The values of material properties for the tailings evaluated for *Hardening Soil* can be seen in Table 1. By using *Hardening Soil*, in the analyses, deformations could be realistically modeled, since *Hardening Soil* is a better constitutive model than the simpler constitutive model

Table 2 Values of material properties for filter, rockfill and till in the dam structure in Figure 2 (Sweco Infrastructure AB and TCS AB, 2012; Jonasson, 2008). The material properties are defined in e.g. Brinkgreve et al. (2014).

	Unit	Filter	Rockfill	Till (starter dike)	Till (underground)
E	kPa	20000	40000	20000	20000
ν	-	0.33	0.33	0.33	0.33
c'_{ref}	kPa	1	1	1	1
φ'	°	32	42	35	37
ψ'	°	0	0	0	0
γ_{unsat}	kN/m^3	18	18	20	20
γ_{sat}	kN/m^3	20	20	22	22
e_{init}	-	0.5	0.5	0.5	0.5
k_x	m/days	86.4	0.1	0.00864	0.00432
k_y	m/days	86.4	0.1	0.00432	0.000864

Mohr Coulomb when analyzing deformations (Brinkgreve et al., 2014).

The constitutive model *Mohr Coulomb* was chosen for filter, rockfill and till since values of material properties were available, see Table 2. The values of material properties for the *Mohr Coulomb* model were provided from geotechnical investigations reported by Jonasson (2008).

All values used as material properties in the simulations were assumed to be valid also in the future. No studies about future behavior of this tailings material have been composed; for instance, regarding changes of stiffness and strength caused by aging effects.

The increased load from the dike constructions is first carried by the pore water in the form of excess pore water pressures. The excess pore water pressures will then slowly decrease during consolidation and the load transforms gradually over to the soil skeleton. The hydraulic conductivity in the soil material and drainage conditions in the surroundings determines the rate of excess pore water pressure dissipation. This is modeled in PLAXIS 2D for each activity, by first assuming undrained conditions that will change into drained conditions if complete consolidation is achieved.

3.3 Mesh generation

The geometry of the tailings dam was divided into 15-noded triangular finite elements. In order to choose a proper mesh, different element coarseness were tested in the simulations. The most convenient mesh was chosen considering both computation time and accuracy of the results, see Figure 3. Local mesh refinements were performed in the downstream toe of the dam to achieve more accurate results in the computations.

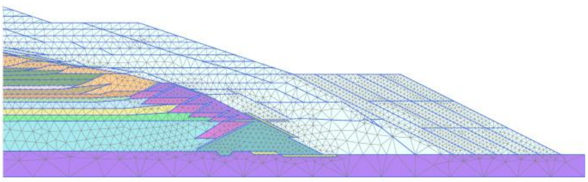

Figure 3 Generated mesh in the model with local mesh refinements at the dam toe.

3.4 Computation phases

All computations in the software PLAXIS 2D were defined with initial conditions, described in an initial phase at a pre-defined time. This initial time point for the studied tailings dam E-F was chosen to be in year 2007, since the raising rate of the dam increased that year. It was assumed, due to the low raising rate earlier, that no excess pore water pressures existed in the dam structure at the defined initial time point. All deformations were set to zero in the initial phase.

One year was divided into different activities that were inserted in the simulations as computation phases, see Figure 4. Between the period 15th of October and the 30th of April, no discharge of tailings from dam E-F was taking place. This period is called winter in Figure 4. In the vicinity of the analyzed cross section, it was assumed that spigotting of tailings took place between the period 1st of May and 31st of July. Followed by a period of 15 days of rest, 15 days of dike construction and another 15 days of rest. The rests were needed for the working process for dike constructions. After that, spigotting continued 14th of September until 14th of October.

Month	Activities
January	Winter (120 days) (121 days if leap year)
February	
March	
April	
May	Spigotting (91 days)
June	
July	
August	Rest (15 days)
	Dike construction (15 days)
September	Rest (15 days)
	Spigotting (31 days)
October	
November	Winter (78 days)
December	

Figure 4 Annual activities at dam E-F used in the computations.

In order to assess the slope stability of tailings dam E-F, consolidation computations were executed. The times defined in Figure 4 correspond to the duration of each activity where consolidation was computed. The worst case was found when the load increased within the dam structure and consolidation was still not completed. This occurred immediately after a new dike was constructed. The increased load gave increased excess pore water pressures and thus decreased *FoS* values.

With the intention of examining the dam stability, safety computations were performed after each consolidation computation. The factor of safety is defined in PLAXIS 2D by

$$FoS = \frac{available\ strength}{strength\ at\ failure} \qquad (1)$$

where the *available strength* is the strength from the effective stress state and input strength parameters. The *strength at failure* is obtained by decreasing the input strength parameters in small increments until an unstable structure is obtained. The *FoS* assessed in PLAXIS 2D gives the global *FoS* of the whole dam geometry. (Brinkgreve et al., 2014)

3.5 Water conditions

The phreatic line defined in the simulations was assumed to be at the surface of the tailings material, see a), b) and c) in Figure 5 depending on the activity described in Figure 4. As can be seen, the location of the phreatic line was changing depending on the activity. When the phreatic line reached the point where the beach and the dike construction intersects (dike toe) the groundwater level started to incline as a straight line between fixed measurement points in the dikes, see d) in Figure 5. Thereafter, the phreatic line was assumed to be horizontal. This level represents the highest allowed water level in the clarification pond. The field measurements regarding ground water location were provided by Boliden Mineral AB.

4 RESULTS

Stability analyses were conducted to assess the future stability of the studied tailings dam. The stability of the tailings dam, subjected to raisings, was first analyzed without rockfill berms added on the downstream slope of the dam. The result indicated a trend of decreasing *FoS*. Strengthening actions were therefore required. This was modeled by adding rockfill berms on the downstream slope.

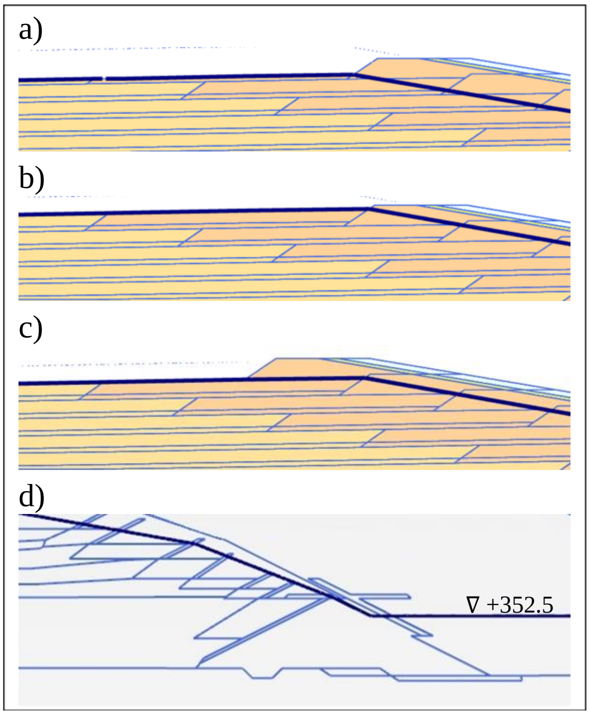

Figure 5 Location of the phreatic line: a) between 14th of September and 30th of April b) between 1st of May and 14th of August c) between 15th of August and 13th of September d) in the dam toe during all activities.

4.1 Stability with no strengthening methods

The studied raisings of the tailings dam were simulated without any strengthening methods on the downstream slope of the dam to investigate if sufficient stability was obtained. It was shown in the simulations that after only three years the *FoS* was decreasing to values continuously below the recommended value of 1.5. Since the *FoS* did not fulfill the recommended value no further analyses without strengthening methods were performed. The result from these simulations gave the *FoS* shown in Figure 6.

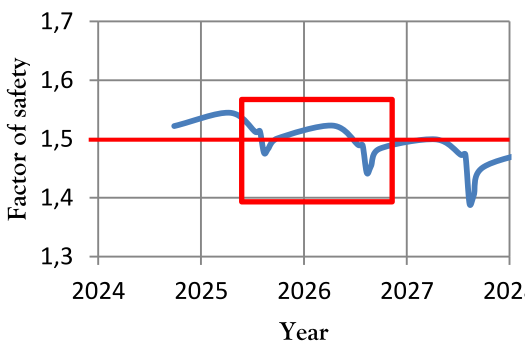

Figure 6 Values of FoS with no rockfill berms added on the downstream slope of the dam.

The highest computed *FoS* value each year occurs when maximum consolidation is achieved, due to decreased excess pore water pressures in the dam structure, see a) in Figure 7. Maximum consolidation is obtained immediately before spigotting in the spring i.e. 30th of April. When the spigotting begins, 1st of May, the *FoS* starts to decrease. This phenomenon occurs because of increased load from newly deposited tailings. The increased load contributes to excess pore water pressures and thereby reduced stability. Later in August when a new dike construction takes place, the *FoS* makes a rapid drop due to increased load which contributes to excess pore water pressures in the dam, see b) in Figure 7. The lowest *FoS* corresponds to the time when maximum excess pore water pressures are obtained, see c) in Figure 7. When consolidation of the tailings material continues after a dike is constructed, the *FoS* starts to increase again.

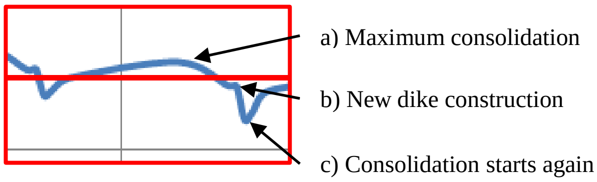

Figure 7 Enlargement of the red rectangle in figure 6. a) maximum consolidation in the soil is obtained, b) load from a new dike construction is applied, c) the soil begins to consolidate, highest values of excess pore water pressure are also find in this phase.

The most critical slip surface in year 2027, associated with the lowest *FoS*, occurred directly after a new dike was constructed, see Figure 8. The slip surface is located in the upper part of the downstream slope of the dam and the shape is almost circular. Since the *FoS* is below the recommended value of 1.5, the dam structure was further investigated by adding rockfill berms on the downstream slope of the dam.

4.2 Stability with strengthening methods

The *FoS* from the simulations with rockfill berms added on the downstream slope of the dam can be seen in Figure 9. The figure shows that the *FoS* for the whole time period studied are above the recommended value of 1.5. It can also be noted in Figure 9 that the annual distribution of the values of *FoS* is very similar each year. The highest value of the *FoS* occurred when maximum consolidation was achieved and the lowest value of the *FoS* was achieved immediately after a new dike construction, due to increased load giving increased excess pore water pressures. The positions of the added rockfill berms can be seen in Figure 10. The rockfill berms added on the downstream slope of the dam increased the *FoS* so that values above the recommended value were obtained in all computation phases.

The slip surface representing the lowest *FoS* in year 2027 with rockfill berms added on the downstream slope of the dam can be seen in Figure 11. The slip surface is located deep, throughout the whole dam body and embraces a much larger volume of soil than the slip surface in Figure 8. The slip surface obtained in Figure 11 is non-circular.

The volumes of rockfill modeled in the simulations, during winters, on the downstream slope of the dam can be seen in Figure 12. The volumes were calculated with a constant dam length of 1500 meters. Thus, the south end of the dam consists of another dam and the north end of dam E-F consists of a dam corner, see Figure 1. It was noted that different volumes of rockfill were needed different years to obtain values of the *FoS* above the recommended value. Between the years 2030 and 2033, larger amounts of rockfill were needed compared to the other years studied.

5 CONCLUDING REMARKS

It was shown that if no rockfill berms were added on the downstream slope of the dam the slip surfaces were almost circular and located in the upper part of the dam structure. However, the factor of safety, *FoS*, gradually decreased below the recommended value of 1.5 as the dam was raised.

Strengthening actions were required to obtain values of the *FoS* above the recommended value. Rockfill berms were thus added in the simulations on the downstream slope of the dam structure.

It was stated that with enough rockfill berms on the downstream slope of the dam the stability between the years 2024 and 2034 was sufficient according to the recommended value of 1.5. When rockfill berms were added on the downstream slope of the dam the values of the *FoS* increased and the shape of the slip surfaces changed, they started to go deep through the whole dam and embraced larger volumes of soil.

The distribution of the *FoS* has a similar trend during each year in the analyses with rockfill berms. The *FoS* are located above the recommended value in all simulations which

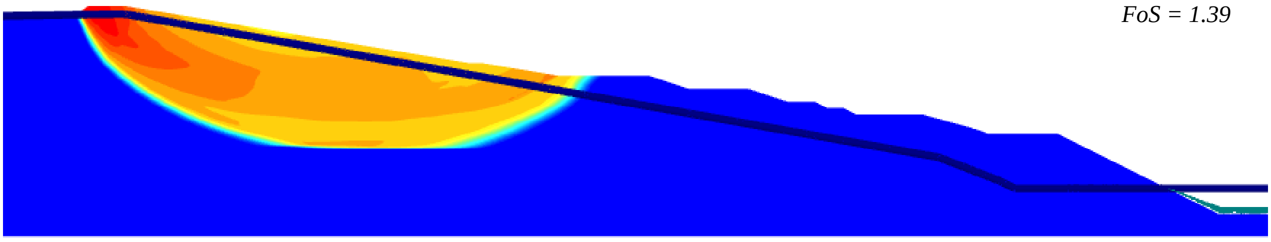

Figure 8 The most critical slip surface after dike construction year 2027; without any rockfill berms added.

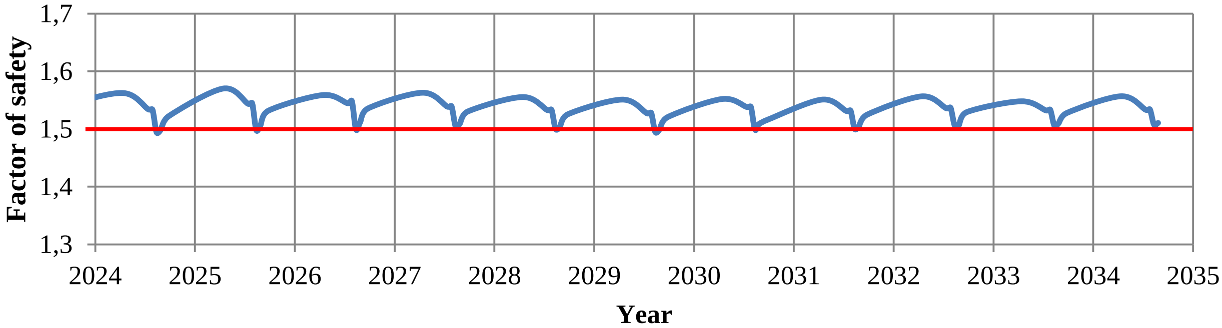

Figure 9 FoS when rockfill berms were added on the downstream slope of the dam.

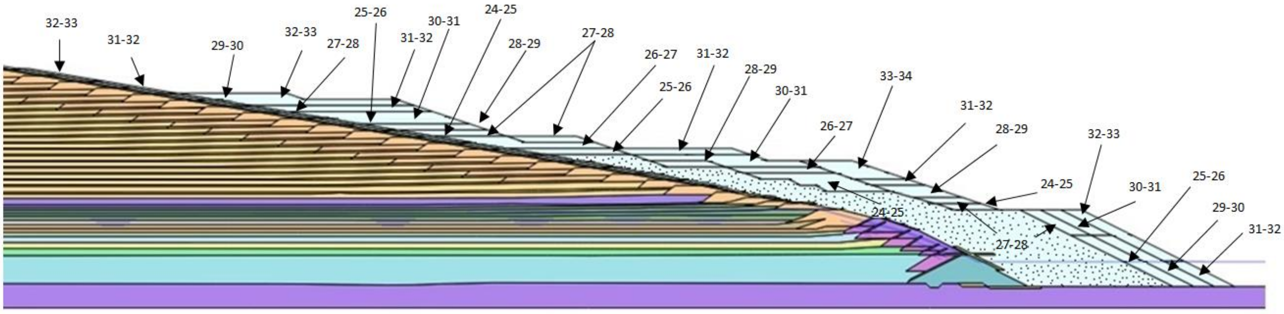

Figure 10 Rockfill plan for future raisings at the studied dam E-F.

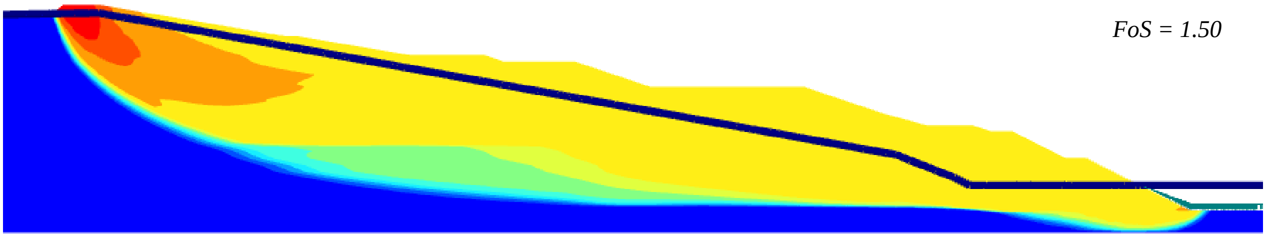

Figure 11 The most critical slip surface after dike construction year 2027; with rockfill berms added.

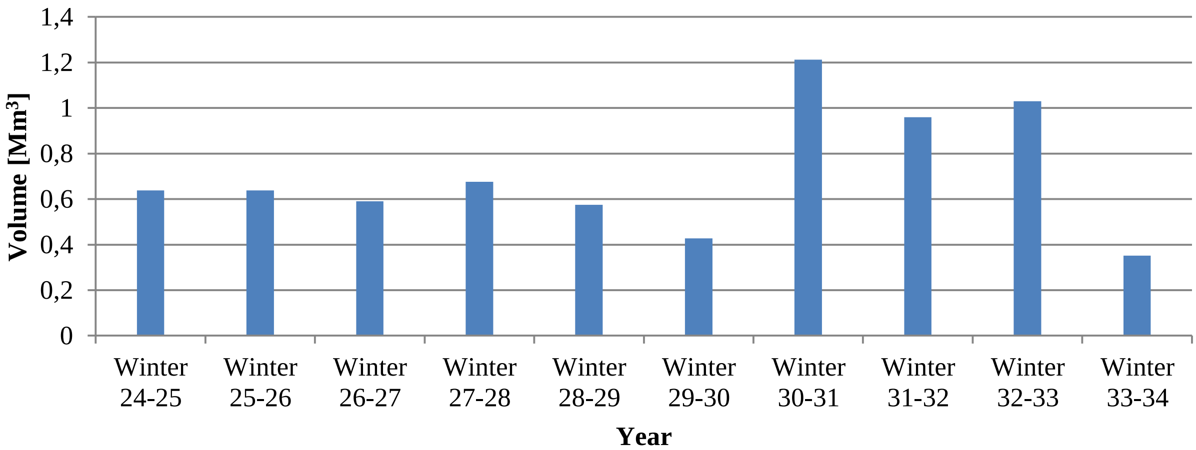

Figure 12 Volume rockfill used on the downstream slope of the dam in the simulations.

indicated that a good optimization of rockfill berms was performed.

Different volumes of rockfill had to be added each year in order to increase the values of *FoS*. The increased dam stability comes from the resisting moment of the added berms and if longer distances, i.e. levers, between the point of rotation and the point of gravity in the berms were utilized, less amount of rockfill had to be used.

Once a geometry of a structure was inserted into a finite element software it is easy to do further investigations and analyses, by stepwise add or remove soil volumes to the structure. Thus, gradual raisings of a tailings dam is a good example of an engineering application that is particularly suitable to analyze in a finite element software.

This study has shown, that the finite element software PLAXIS 2D is a very good tool in finding the most convenient locations as well as volumes for rockfill berms to be added, using stability analysis when raising tailings dams.

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