NUMERICAL MODELLING FOR STABILITY OF TAILINGS DAMS

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Summary

A tailings dam is a large embankment structure that is constructed to store the waste from the mining industry. Stability problems may occur in a tailings dam due to factors such as quick rate of raising, internal erosion and liquefaction. The failure of a tailings dam may cause loss of human life and environmental degradation. Tailings Dams must not only be stable during the time the tailings storage facility is in operation, but also long time after the mine is closed. In Sweden, the licensing authorities demand that the tailings dams should be stable up to the next glaciation age, which is interpreted to be 1000 years or more. This goal requires extensive knowledge in order to be able to design the tailings dams so that they can be stable for such a long time. At the Division of Mining and Geotechnical Engineering at Luleå University of Technology, research has been conducted on the stability of tailings dams, using the finite element method which is considered to be suitable for modelling the complex geometry and the material properties of tailings dams. A case study is presented which describes the application of the finite element method in evaluating the stability of a tailings dam.

1 INTRODUCTION

In this paper a case study is presented on the use of the finite element method to evaluate the stability of the Aitik Tailings dam located near Gällivare in Sweden. The intention is to give an example of how advanced computer based numerical tools can be used to study the slope stability of dams. Commercial computer programs, based on the finite element method, are being utilized for the design of complex geotechnical structures and it is assumed that these programs will be increasingly used in the future when
more and more students with skills in this type of software will enter the labour market.

The finite element method is a numerical approach to approximately solve the differential equations that describe physical phenomena in mechanics. In geotechnical engineering, the main advantages of the finite element method compared to traditional hand calculation methods are (i) the shape or location of the failure surface is not assumed in advance and failure occurs through such zones in the soil where the shear strength is lowest and (ii) the problem can be solved in a physically more accurate manner.

Stability analyses have been performed on the Aitik tailings dam with the commercial software PLAXIS, which is a finite element program for analyses of stability and deformation of geotechnical structures. Modelling principles described in this paper are not only specific to the Aitik but can also be used for other tailings dams.

2 TAILINGS DAM IN AITIK

Aitik is a copper mine located approximately 15 km south-east of Gällivare in the north of Sweden. The mine is owned by Boliden AB and is today one of the largest copper mines in Europe and the largest open pit mine in Scandinavia. The mining activities started in 1968. The annual production at the Aitik mine was about 31.5 million tonnes of ore in year 2011.

Tailings are obtained as a by-product when the valuable metals are extracted from the ore. The grain size of the tailings varies from medium sand to clay size. In Aitik, tailings are pumped to the tailings disposal area where they are discharged from several points along the dam crest. Figure 1 shows the tailings impoundment which occupies an area about 13 square kilometres. In this impoundment, there are four dams: A-B, C-D, E-F (including extension E-F2) and G-H. The clarification pond is located downstream of the dam E-F.

The dams are being mainly raised in stages with the upstream construction method, which is considered to be simple and economical in cost. In a dam raised with the upstream construction method, new dikes are built mainly on the previously deposited tailings. This can lead to high excess pore pressures and low shear strengths in the deposited tailings if the dam is raised too
quickly. In this situation, rockfill berms can be used as supports on the downstream side to ensure the stability of the dam.

Figure 1. Aerial view of the tailings storage facility in Aitik.

3 NUMERICAL ANALYSES
Numerical analyses with the finite element program PLAXIS have been carried out on the dam section E-F to minimize the volume of rockfill berms that were needed to maintain enough slope stability of the dam.

The corner between the dam sections E-F and G-H (Figure 1) has also been analysed with the finite element program PLAXIS to identify zones of low compressive stresses or tensile stresses and to evaluate slope stability.

3.1 Analyses of dam E-F
The geometry and material zones of the dam E-F are shown in Figure 2. The elevation of the dam was 391 m in year 2012. The dam will be raised to a height about 410 m in year 2018. It was assumed that the tailings are stored in the impoundment at a rate of three meters per year. The raising of the dam was simulated in eleven stages. Each stage consisted of a raising phase over 10 days and a consolidation phase over 355 days.
The analyses of dam E-F have been performed with a plane strain model by assuming that there are negligible deformations in the longitudinal direction of the dam. Furthermore, the boundary conditions for deformation and water flow have been assigned and the location of the phreatic level has been determined based on field tests. A very central component of the finite element method is the constitutive relationship which describes the stress strain behaviour of soils. A user of PLAXIS must choose an appropriate constitutive model for each soil type and enter values for the parameters included in the model. When selecting a constitutive model and its input parameters, it is very important to remember that the model must be able to simulate the soil behaviour well enough; otherwise, realistic results cannot be obtained from the analyses. In this study, the Mohr-Coulomb model was used for all the soil types and the model parameters were determined by laboratory and field experiments. A sufficiently fine mesh was chosen to obtain results with enough accuracy, see Figure 3.
According to Swedish tailings dams’ safety guideline document GruvRIDAS, a safety factor larger than or equal to 1.5 was used as a slope stability criterion for the dam. The analyses were initially carried out on dam E-F with a model geometry including the previously existing rockfill berms (Figure 4). As the dam was gradually raised, the safety factors were reduced due to increase in disturbing moment and excess pore pressures (Figure 5). Additional rockfill berms were placed on the downstream side so that the dam can be raised with enough safety. Figure 5 shows the safety factors for the two scenarios, i.e., (i) with previously existing rockfill berms and (ii) with additional rockfill berms on the downstream side.

An optimization analysis was also performed in order to obtain sufficient stability of the dam by using minimum volume of rockfill berms. Figure 6 shows the rockfill berms (P, Q, R, S, T, U, V and W) that were needed to maintain stability of the dam.

This example shows that the finite element based optimization technique was very useful to achieve enough slope stability by using a minimum volume of rockfill berms, which can lead to significant savings related to construction costs.

*Figure 4. Cross section of dam E-F with only previously existing rockfill berms on the downstream side.*
Figure 5. Factors of safety for all the raising and associated consolidation phases (here the terms R and C represent the raising and consolidation phases, respectively).

Figure 6. Placement of rockfill berms (P, Q, R, S, T, U, V and W) on the downstream side to ensure enough slope stability during gradual raisings of the dam E-F.
3.2 Analyses of the corner E-F/G-H

The corner E-F/G-H has a curvature where the horizontal pressure of the stored tailings acts from the inside of the dam structure against the curve which bends outwards, see Figure 1. A corner is a potentially weak structure where low compressive stresses or even tensile stresses may occur in the longitudinal direction. The occurrence of such low compressive stresses or tensile stresses in the corner depends on factors like geometry and material properties.

Low compressive stresses in the dam corner may give rise to soft zones which may be susceptible to internal erosion. Tensile stresses in the dam corner can cause cracks. Internal erosion may occur through the cracks in the dam. Internal erosion is a process in which the water that seeps through the dam carries soil particles away from the embankment or the foundation.

The material properties of the corner E-F/G-H are similar to those of the dam E-F. The modelling procedure, which was previously described for the dam E-F, was also applied to the corner. Due to the complex geometry of the corner, a three dimensional finite element program PLAXIS 3D was utilized to investigate the stress conditions and to evaluate slope stability. The three dimensional model of the corner is illustrated in Figure 7.

The corner was also analysed with a two dimensional axisymmetric finite element model on the assumption that the corner is similar to a circular structure. The results from the 2D axisymmetric analyses were compared with the results from the 3D analyses. The purpose of the comparison was to check the reliability of the 2D axisymmetric finite element model for this complicated geometry of the corner.

The results from both the 3D and 2D analyses indicated that the stress conditions in the dam seemed to be satisfactory to prevent the development of soft zones or cracks in the dam. It was also interpreted that there was no increased risk of internal erosion in the dam corner.

Another conclusion drawn from this study was that the results from the 2D axisymmetric analyses are consistent with the results from the three dimensional analyses. This is an important finding because a significant
amount of computational time can be saved by using a 2D axisymmetric analysis instead of a 3D analysis.

Figure 7. Three dimensional model of corner E-F/G-H.

3.3 Dynamic analyses of the dam E-F
Currently at the Division of Mining and Geotechnical Engineering at Luleå University of Technology, there is on-going research regarding the behaviour of the Aitik tailings dam subjected to shaking from earthquakes. The dynamic module of the finite element program PLAXIS 2D was used. A possible danger of an earthquake is that liquefaction may occur during cyclic loading, especially if the tailings are loose and saturated with water. Liquefaction results in a rapid decrease in the shear strength of the tailings when the excess pore pressures increase due to seismic shaking. Large displacements may occur in liquefied zones in the dam where the shear strength of the tailings is reduced significantly. A failure of a tailings dam may occur, if large zones in a dam liquefy. Several tailings dams located in Chile, Japan and Peru have failed as a result of liquefaction due to seismic shaking.

Two earthquakes of different magnitudes were selected to predict the seismic behaviour of the Aitik tailings dam. Two scenarios are considered, i.e., (i) an
earthquake of high magnitude (an extreme case) and (ii) an earthquake of low magnitude (a normal case).

As the extreme case, the input was used from an earthquake of magnitude 5.8 that occurred in 2011 in the state of Virginia in the eastern United States. This earthquake is chosen on the assumption that the eastern United States and the northern Sweden have similar geologic and seismic behaviour. Figure 8 shows the seismic input data to PLAXIS for the extreme case. The data for the Virginia earthquake was obtained from the organization U.S. Geological Survey. Input data for the normal case is selected from an earthquake of magnitude 3.6 that occurred in 2011 outside Skellefteå in northern Sweden.

Because this study is not yet completed, the results of the dynamic analyses are not presented here. But it will be interesting to observe later if the above mentioned earthquakes can have any influence on the stability of the Aitik tailings dam.

![Figure 8. Acceleration-time record of the earthquake in Virginia in 2011.](image)
4 CONCLUDING REMARKS

The finite element method has been utilized for a case study on the Aitik tailings dam. The dam is being constructed in accordance with the findings from the finite element analyses performed. An advantage of the finite element method is that once a finite element model is developed it can be easily modified; for example to include future raisings of a tailings dam. It is hoped that, in the future, the finite element method will be used more frequently for the analyses of various geotechnical structures, including tailings dams. Presently, at the Division of Mining and Geotechnical Engineering at Luleå University of Technology, more research is in progress regarding stability of tailings dams, using the finite element method. In addition to this, courses related to finite element modelling in geotechnical engineering are also offered at the Division. More details about our research on the stability of tailings dams can be found in our papers on the subject, published mostly in international journals.