Assessment of the tailings settlement and influence on cap design

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Abstract

Closure planning and closure design consider the activities and tasks which will enable a facility to behave, in line with the closure objectives, in the short- and long-term.

The closure objectives are well identified within society and mining industry and they generally cover key issues that need to be included during evaluation of closure planning and design. They include social impact, environmental concerns, structural integrity and stability, landscape design, final land usage, economical implication, etc.

One of the critical issues in achieving the closure objectives for tailings storage facilities (TSF) is related to the behaviour of the tailings within the facility. There are many factors influencing the short- and long-term behaviour of tailings.

This paper uses broad assumptions based on limited data about tailings properties as homogeneous and simple one-dimensional models to simulate conditions within the Garpenberg TSF influencing the tailings settlement and, finally, on cap design.

Based on the limited data available at this stage, preliminary assessment of the settlement was conducted using assumptions about the tailings properties and the water levels within the facility. A simplified method for prediction of deformation within a facility (consolidation and settlement) was carried out using a one-dimensional model. The software SIGMA/W, which performs stress and deformation analyses of columns (column test), was used to analyse various thicknesses of the tailings within the facility.

Three components of the deformation were considered: consolidation after tailings deposition, settlement due to changes of water level within the facility and settlement caused by loading of capping layers. They were assessed separately, and final deformation was obtained by superposition of the estimated values.

In addition, the feasible options for final cap shape are discussed, and so is how to take settlement into consideration during the design.

Keywords: *tailings conditions, consolidation, settlement, cap design*

1 Introduction

The settlement of tailings within a tailings storage facility (TSF) is a complex process which depends on the tailing's properties, thickness of the deposited tailings, deposition strategy, conditions with respect to the decant pond size and location, change of water levels within the facility, degree of saturation and drainage conditions. Most of the factors vary within the facility and are changing over time.

Understanding tailings behaviour and changing conditions within the facilities during deposition is fundamental to evaluate the total settlement of the tailings surface once the facility becomes inactive.

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The total settlement of the tailings surface comprises the following:

- primary consolidation settlement

- secondary consolidation settlement (creep) – not considered in this study

- desiccation process – not considered in this study

- settlement due to changes in loading conditions:

  ○ settlement due to water drawdown within the facility

  ○ settlement due to surcharge load caused by cap construction (covering layer).

Based on the limited data available at this stage, preliminary assessment of the settlement has been conducted using assumptions about the tailings' properties and the water levels within the facility. A simplified method for prediction of settlement within the facility was carried out using a one-dimensional model. The software SIGMA/W and the column method were used to analyse various thicknesses of the tailings within the facility to predict stress and deformation of the TSF over time.

1.1 Description of study area

The Boliden operated Garpenberg TSF is approximately 4.5 km around its perimeter and covers an area of about 1.5 km^2 as indicated in Figure 1. The tailings that are not used for backfilling in the Garpenberg mine are deposited hydraulically into the TSF.
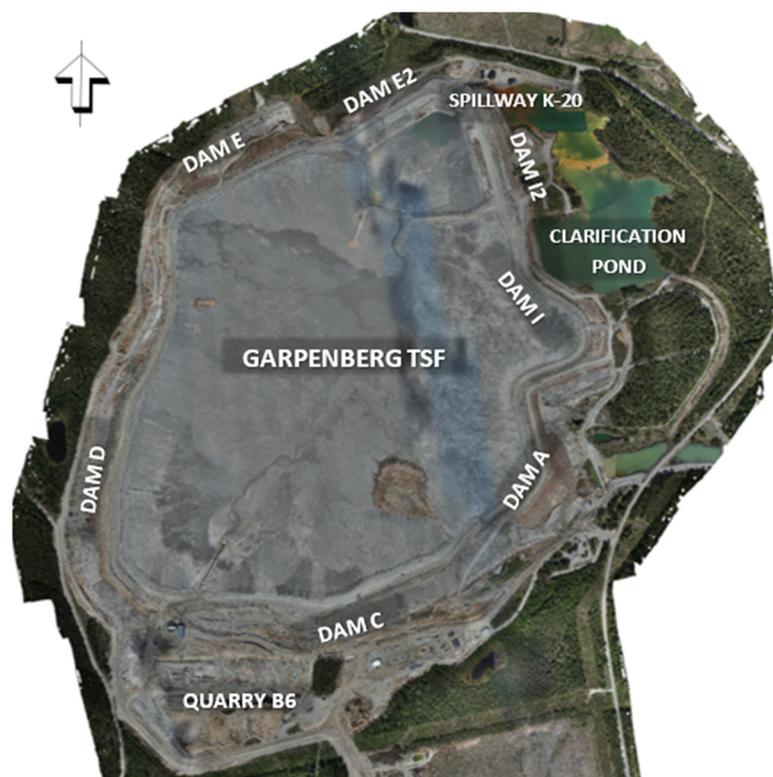

Figure 1   Overview of Garpenberg tailings storage facility

1.2 History of the site

Deposition began in 1965 in an existing lake together with the first dam construction. Tailings deposition started with end-pipes and underwater deposition. As the height increased, the various perimeter were built and today the TSF is surrounded by dams along the entire perimeter. In the 1990s, deposition started with multiple spigotting points around the perimeter forming the tailings beaches. Historic changes of the Garpenberg TSF are presented in Figure 2.
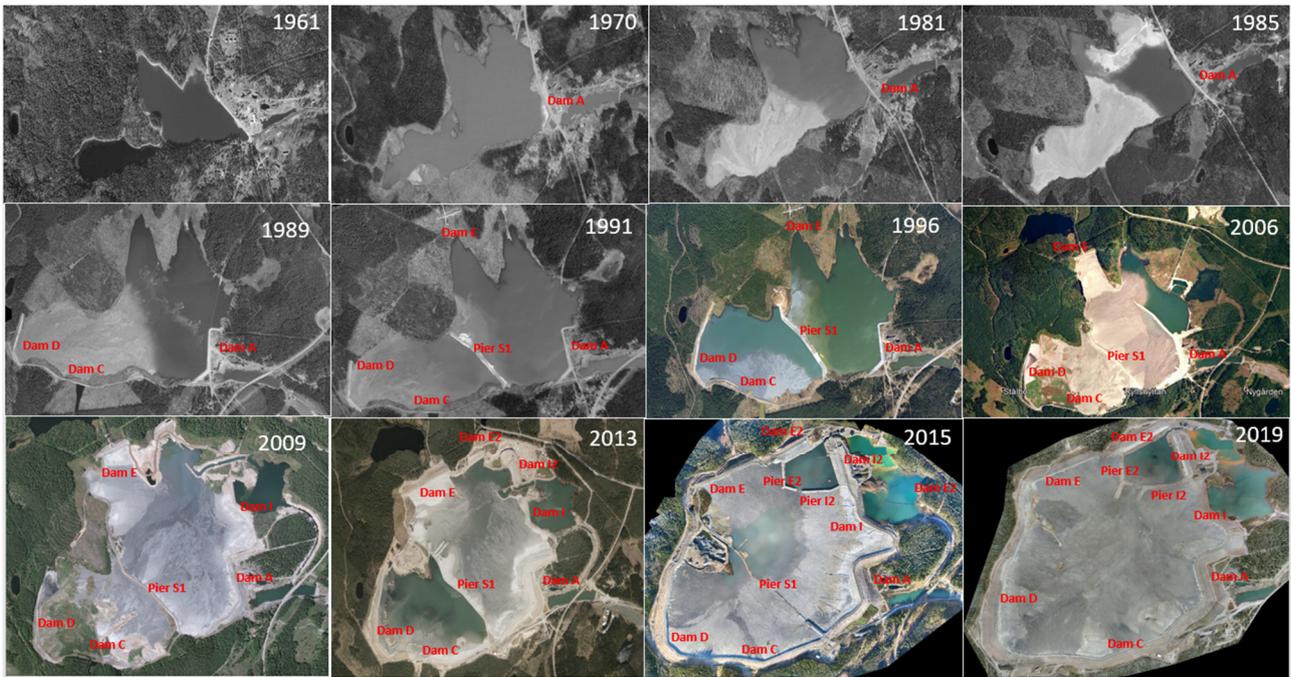
Figure 2   Development of Garpenberg TSF between 1961 and 2019

Due to the site morphology and changes in deposition methods, the tailings conditions within the facility vary. The early tailings deposited underwater are saturated and loose, whereas the tailings deposited later by spigotting are coarser, more consolidated and have a decreasing pore pressure toward the perimeter. In the middle of the TSF, the tailings remain saturated and loose.

1.3   Analysed cases

Based on the site conditions, the pattern of tailings deposition, and the depth of the tailings, the settlement evaluation was focused on profile D-A and profile C-spillway. The positions of the analysed profiles are depicted in Figure 3.
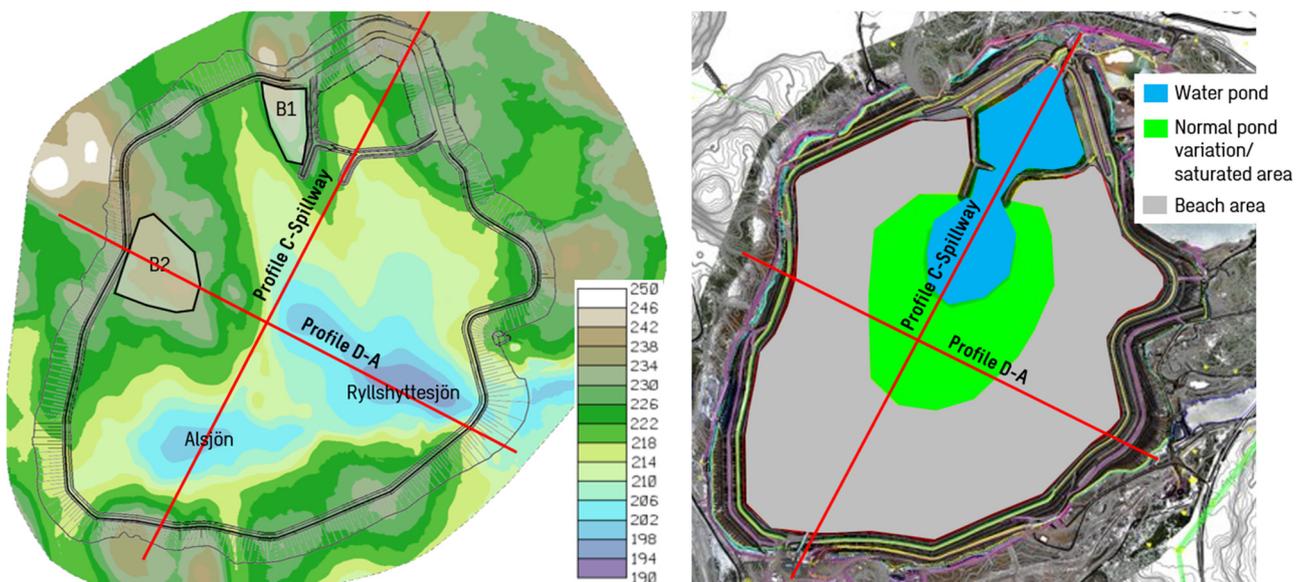

Figure 3   (a) Overview plan – topography before deposition with analysed sections (B1 and B2 refer to old rock quarries); (b) Overview plan – estimated final shape of tailings storage facility with analysed sections and location of water pond

Different sections (columns) were selected along these profiles (Figures 4 and 5), and each section is evaluated as an independent column (one-dimensional model).
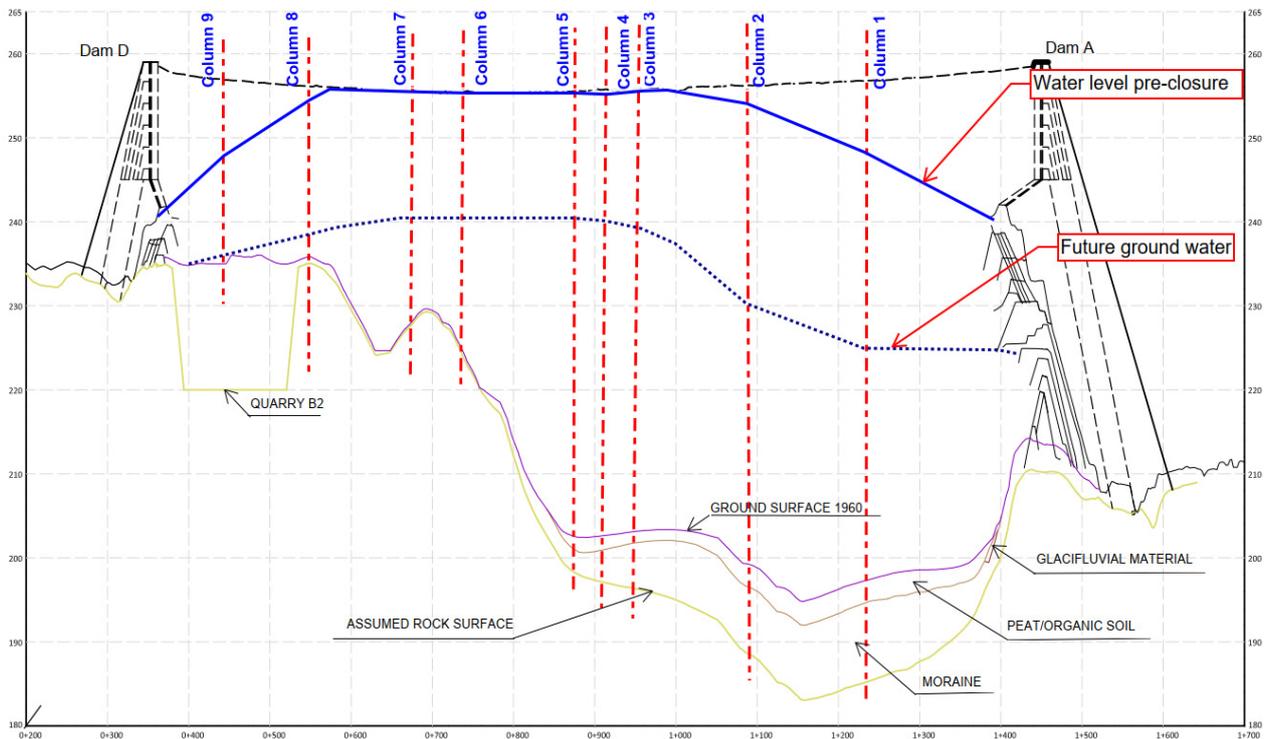

Figure 4   Positions of representative columns along profile D-A
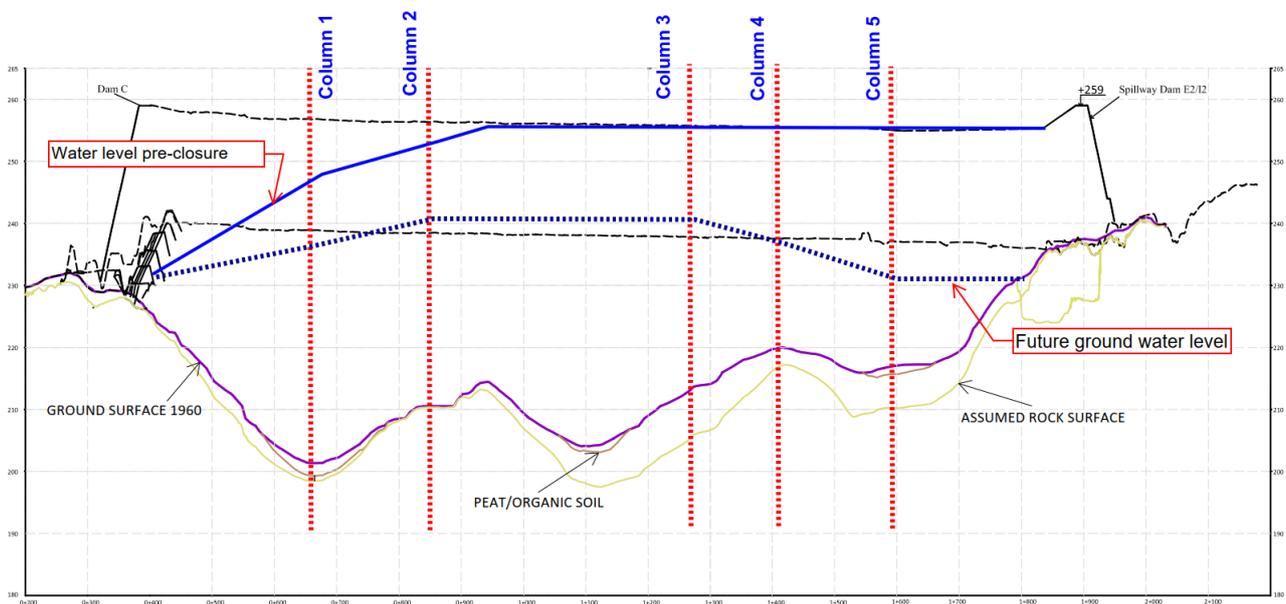

Figure 5   Positions of representative columns along profile dam C-spillway

2   Methodology

Settlement analyses were conducted using SIGMA/W. SIGMA/W is finite element software used for analysing stress–strain responses in geotechnical systems.

SIGMA/W was used to simulate the staged depositions of tailings, where tailings are deposited in layers over time.

SIGMA/W solves two-dimensional soil consolidation problems by using fully coupled analysis. In this analysis, each node of element grid (mesh) is assigned three equations, two of which concern the displacements (horizontal and vertical) while the third expresses the flow. Variations of displacement and porewater pressure is determined by solving these three equations simultaneously.

To calculate settlement using SIGMA/W, the following inputs are required:

1. Tailings material parameters based on the selected soil behaviour model. In this case, to simplify the consolidation modelling process given limited information about tailings properties, the tailings model was selected as an elastic soil model. Therefore, elastic modulus and Poisson's ratio are the main parameters needed.

2. Initial conditions, including the tailings' initial void ratio and density.

3. Boundary conditions, including drainage and loading conditions. Since most of the TSF is founded on bedrock or moraine with low permeability, allowing only one drainage pathway, in this analysis, one-way drainage upwards with incremental tailings deposition per year has been adopted.

A simplification in the modelling has been done by assuming full saturation of the tailings within the facility before closure. As this assumption is very crude, in reality the conditions vary during the life of the facility and consolidation is an ongoing process, a percentual reduction of the settlements due to consolidation has been done based on engineering judgement.

3 Input data

3.1 Material properties for settlement calculation

During the tailings deposition within the facility, the material properties such as particle size, void ratio, dry density, permeability, consolidation coefficient and elastic modulus vary from the perimeter embankments towards the centre of the facility. These variations occur due to the tailings segregation during deposition, varying surface conditions (drying and wetting), different drainage conditions, ongoing operation process within the TSF (usage of the tailings for construction of the perimeter walls), variation in the orebody, and they all significantly influence on the settlement during and post operation. The tailings at Garpenberg has been characterised into three different material types – silt, sandy silt and silty sand (Sweco AB 2021) – with the finest tailings towards the middle of the TSF and in the area of the decant pond, and with the coarser tailings being closest to the perimeter wall due to segregation. Considered to be an average, the sandy silt tailings properties have been used for the analyses in this study.

The adopted tailings properties are presented in Table 1.

Table 1   Material properties for consolidation analysis

Material	Soil behaviour model	Unit weight (kN/m³)	Initial void ratio	Possion's ratio	Elastic modulus (kPa)	Specific gravity, Gs	Permeability (m/s)
Tailings material	Elastic	18.2	1.3	0.3	900	2.97	1E-7

An average elastic modulus for the settlement calculations due to changing of the loading conditions (water level drawdown and surcharge load caused by cap construction) was adopted to be different from the one adopted for the consolidation stage. The elastic modulus was selected to be 7,000 kPa, based on the results obtained from triaxial tests conducted on sandy silt material (Sweco AB 2021) for an average effective stress of approximately 600 kPa in the highest column of 63.5 m.

3.2   Loading conditions

Three deformation components were considered in the study:

1. First component – consolidation (staged deposition): staged deposition of tailings has been simulated by applying incremental loads in steps with the assumption that the tailings are deposited in the layers with variable thickness each year. This scenario assumes that, during each construction phase, the water level is maintained at the top of the newly deposited layer.

2. Second component – water level drawdown: this covers the settlement caused by changing the water levels within the facility which will happen post closure.

3. Third component – external loading: this covers the settlement by a surcharge load of 40 kPa (equivalent to a 2-metre-thick capping layer).

4   Results

The results of the assessment using SIGMA/W for different loading conditions are presented below:

- First component including staged deposition and consolidation:

  ○ Changes of the void ratio is a key indicator of the compressibility of the tailings material. Changes in void ratio reflect how much the tailings compress during its consolidation process. Reduction in void ratio over time and at different depths during deposition for column 3 profile D-A with height of 53.5 m is presented in Figure 6. It can be seen that the deposited layers have been modelled with a 0.5–1.4 m layer thickness per year (50 layers in a period of 50 years) based on the historical data about the storage raises and future prediction.
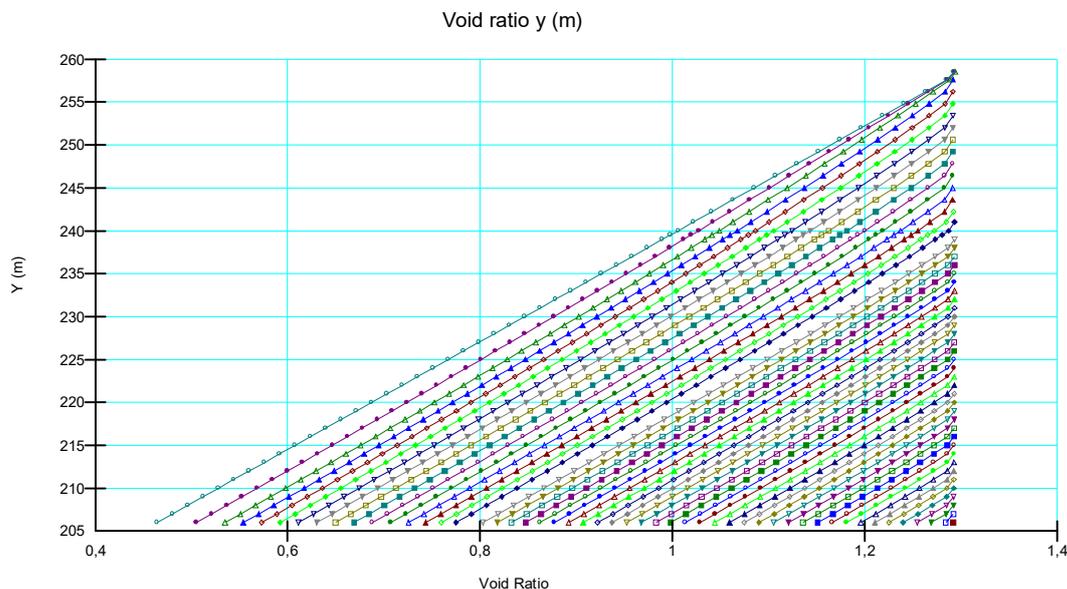

Figure 6   Changes in void ratio at various depths following tailing deposition and pore pressure dissipation – column 3 (profile D-A)

  ○ Pore pressure dissipation time is governed by coefficient of consolidation and drainage conditions; pore pressure dissipates over time as water drains from the material in one or two ways. This directly impacts the rate of settlement. The pore pressure distribution and peak build-up during tailings deposition and dissipation trends over time are shown for the lowest point of tailings material (at the bottom of the facility) for column 3 in Figure 7. The time required for pore pressure dissipation and the completion of consolidation is estimated to be approximately 8 years (based on the adopted tailings properties). An inflection can be observed

at approximately day 12,500 which is due to an estimate that the rate of deposition at that time will increase to 1.4 m per year. As a result, the rate of pore pressure also increases, leading to a steeper inclination of the slope in the upper layers.
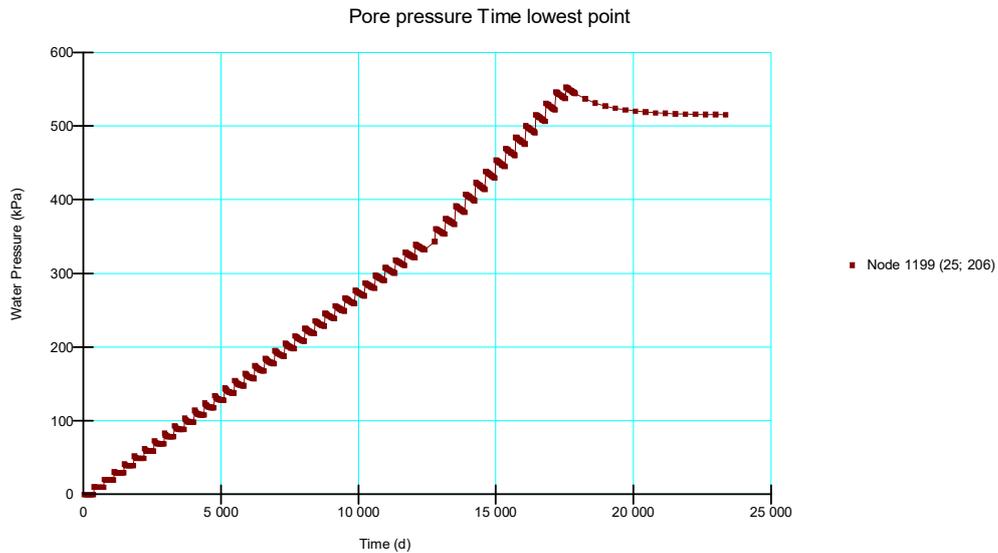

Figure 7 **Pore pressure build-up during tailings deposition and dissipation trends over time – column 3 (profile D-A) at bottom of facility**

○ Consolidation settlement is due to volume change in the tailings as porewater is dissipated and effective stress increases. Consolidation settlement over time at the top point of the selected column 3 (profile D-A) is presented in Figure 8 and the displacement at various depths following the deposition of tailings layers is presented in Figure 9.
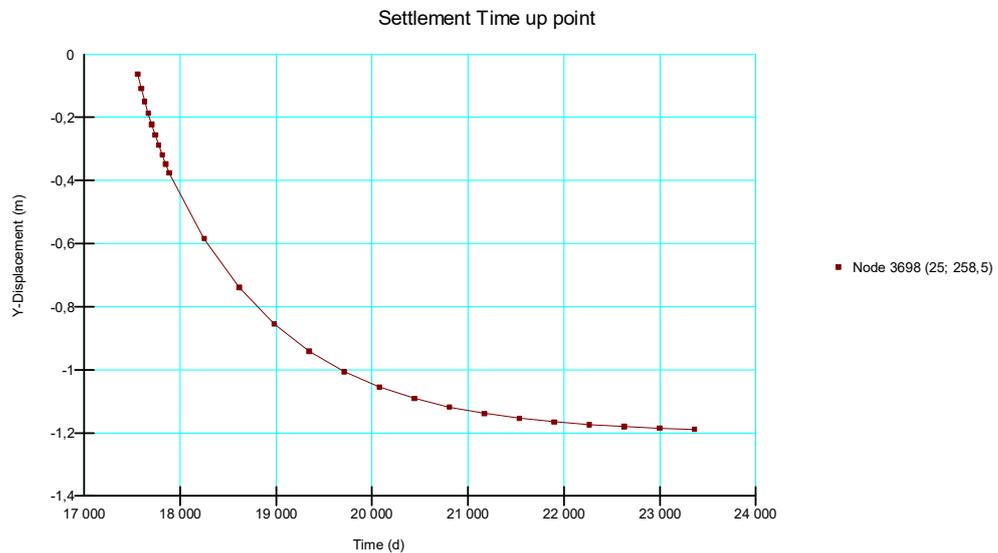

Figure 8 **Consolidation settlement over time at top point of the selected column 3 (profile D-A)**
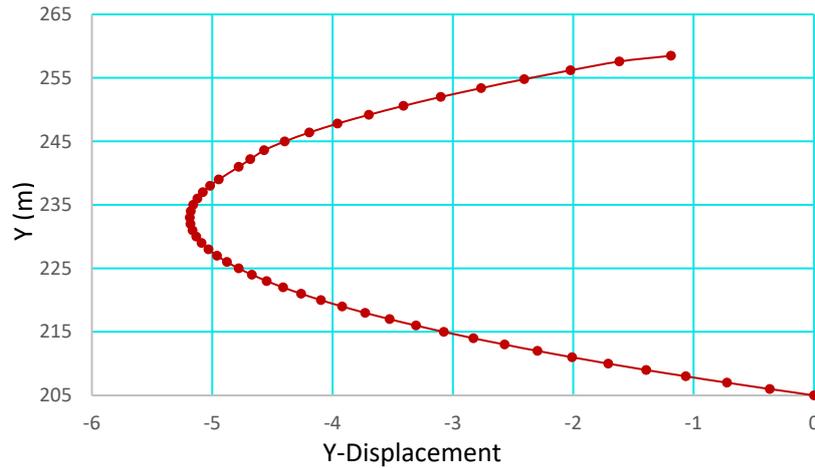
Figure 9   Displacement at various depths following tailing deposition – column 3 (profile D-A)

- Second component, settlement after water level drawdown: after the tailings deposition ceases, the water level will decrease within the facility, leading to an increase in effective stress and additional settlement. Changes of the effective stresses in column 3 (profile D-A) due to the water level drawdown are presented in Figure 10. An initial water level after finishing the tailings deposition is assumed to be +258.5 (fully saturated) and after drainage in the facility is completed (steady state condition) is assumed to be +239.5. The settlement due to water level drawdown and increase in effective stress (around 190 kPa in the middle of column) is estimated to be around 0.9 m in column 3.
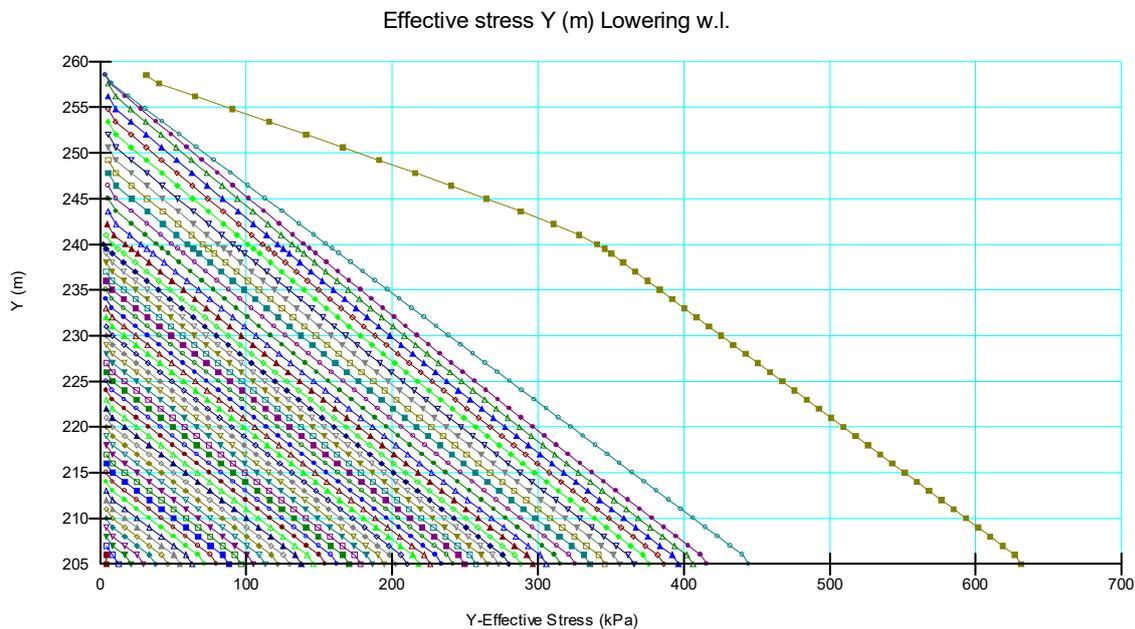

Figure 10   Changes in effective stress at various depths after water level drawdown – column 3 (profile D-A)

- Third component, settlement due to applied surcharge load: by considering the impact of a 2 m thick soil layer as a surcharge load of 40 kPa, the settlements are estimated to be maximum 0.23 m.

4.1   Interpretation of the findings

The estimated total settlements along profile D-A and profile C-spillway are presented in Figures 11 and 12, respectively. Figure 13 illustrates the estimated isoline for total settlement within the tailing facilities in plan view based on the preliminary calculations along the two profiles.

The modelled and calculated consolidation settlements are not representing real site conditions as the tailings are not fully saturated within the facility. Therefore, calculated consolidation settlements are reduced by a certain percentage based on engineering judgement.

Based on the adopted approach, the estimated settlements for the analysed columns are summarised below:

- The maximum portion of the settlement is due to the lowering of the water level within the facility. It is in a range of 31–98 cm in profile D-A, and from 57–83 cm in profile C-spillway.

- The settlement due to the consolidation phase is estimated to be in a range of 3–76 cm in profile D-A and of 18–50 cm in profile C-spillway.

- The settlement due to the surcharge of 40 kPa is estimated to be in a range of 10–25 cm in profile D-A and of 16–26 cm in profile C-spillway.

- The maximum settlement within the facility is estimated to be 185 cm in profile D-A and 160 cm in profile C-spillway.
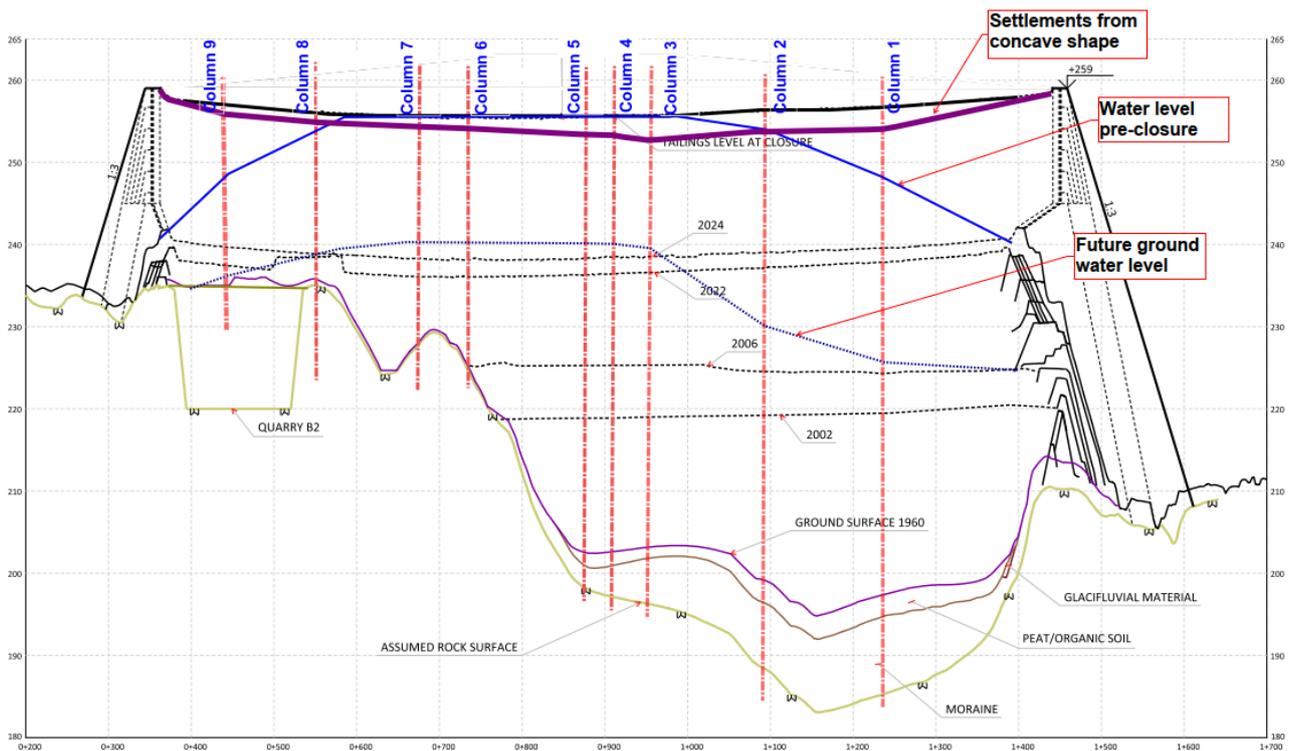

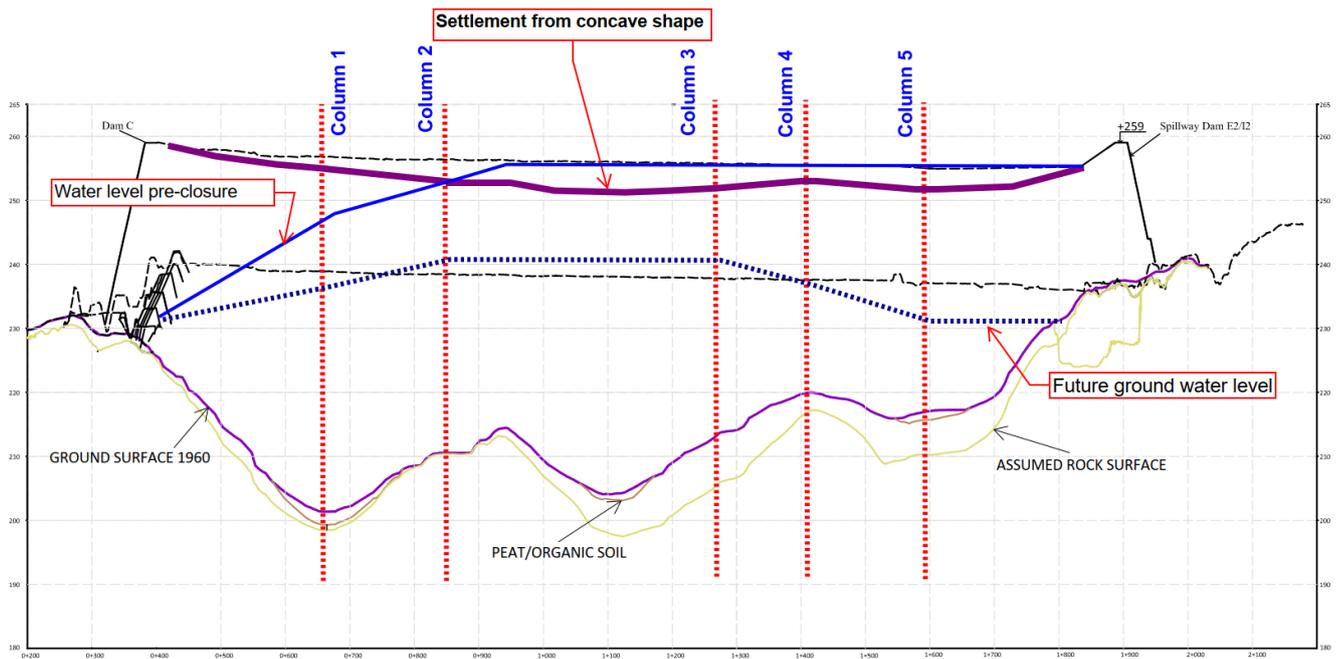**Figure 11   Estimated total settlement along profile D-A**

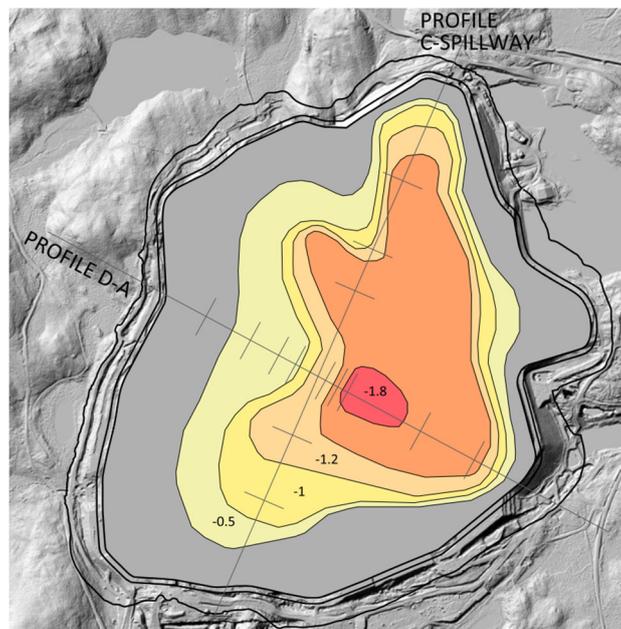**Figure 12 Estimated total settlement along profile C-spillway**

Figure 13 Plan view of estimated total settlement isoline based on preliminary calculation

To enhance more accurate settlement calculations, it is necessary to conduct supplementary investigations within the tailing facilities. For further analyses, the following investigations are recommended:

- further investigation of the tailings properties within the entire facility
- assessment of the conditions with respect to the variations of the water level during operation and boundary conditions with respect to drainage.

A detailed investigation program is currently under preparation which will provide more reliable data for the prediction of the tailings behaviour within the facility. The program includes additional cone penetration tests with porewater pressure measurement (CPTu) for better characterisation of the different zones of tailings within the TSF, as well as consolidation tests for better understanding of large-strain consolidation behaviour.

4.2   Cap design

Evaluation and assessment of the settlement within the facility has an impact on the cap design. Closure design of the TSF encompasses construction of the capping layer to control and reduce oxygen and water reaching the tailings. The cap will be constructed of moraine and/or moraine with bentonite, and as such is sensitive to differential settlements which may cause cracks compromising the function of the cap. The extent of settlement and the consolidation over time is important to take into consideration when planning how to reshape the final surface and when to place the cap.

Three different alternatives for a final cap surface are evaluated in an alternative study:

1. concave shape – in line with the tailings deposition slopes during discharge, collecting water within the facility

2. flat surface – adding some material to flatten surface to minimise collection of water within the facility

3. convex shape – adding more material enabling the surface shape to allow running of water from the cap avoiding and minimising water ponding within the facility.

Differential settlement has a different impact on the alternative cap deigns influencing on the integrity of the capping layer depending on the time of placement of the capping materials and achieved consolidation rate.

The concave shape surface is most sensitive to the differential settlement and consolidation time while, the convex shape is the least sensitive if placement of the cap is done before the majority of settlement is completed. The prediction of settlement is also important to account for to estimate the required volume of material to reshape the surface according to the alternatives.

The work presented in this paper was conducted to help make decisions about cap design and to show the importance of further settlement modelling to better represent real conditions within the facility.

5   Conclusion

A simplified method for prediction of the deformation within the facility was carried out using a one-dimensional model. The software SIGMA/W was used to analyse various thickness of the tailings within the facility by the column method.

Three components of the deformations were analysed: consolidation after tailings deposition, settlement due to the changes of the water level within the facility, and settlement due to additional load of capping layer.

The presented settlements are preliminary and stand for the best estimates considering adopted assumptions of the tailings properties, conditions with the facility, and the modelling approach used.

They provide indicative data to be used for landform design, material planning, and timing for cap construction.

Further refining of the work is recommended addressing the complex processes within the facility influencing tailings properties and settlement within the facility. They vary during the operational time and require detailed site investigation.

Acknowledgement

References

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