Consolidation Modeling for Design of Complex In-pit Tailings Storage Facility

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ABSTRACT: Suitable locations for safe and economic disposal of mine tailings that pose low long-term liability are limited at many mine sites. In recent years, backfilling of existing mine pits with tailings has garnered attention as one viable alternative. The case presented herein, despite having some fundamental resemblance to typical in-pit filling practices, is unique due to the hydrogeology of the area and envisioned complexities of the tailings deposit development within the open pit over the life cycle of the facility. Consolidation modeling was conducted to assess the life-cycle of the facility and the anticipated performance of a proposed intermediate separation layer and overlying geomembrane liner system constructed over soft tailings that are needed to mitigate local groundwater contamination.

Owing to the mine's plan to develop the in-pit Tailings Storage Facility (TSF) as two separate deposits – 1) Lower Deposit, and 2) Upper Deposit – separated by a free-draining separation layer, the consolidation modeling approach consisted of several three-dimensional (3D) and one-dimensional (1D) models using the finite-difference CONDES consolidation software developed at the University of Colorado at Boulder. The first step included development of a 3D consolidation model to assess the anticipated void ratio distribution of the unlined Lower Deposit at the end of deposition within that portion of the TSF. The Lower Deposit is planned to be unlined because the hydrogeology of the area provides a hydraulic sink toward the pit and the groundwater is maintained below a certain level by continuous pumping, which mitigates the potential for groundwater contamination. The Upper Deposit is located above the hydraulic sink elevation and will require a geomembrane liner system to prevent contamination of groundwater sink. This required the design of a rockfill Separation Layer on the surface of the Lower Deposit to account for continued consolidation-settlement of the Lower Deposit and the Separation Layer due to self-weight and filling of the Upper Deposit.

To model this deformation and design the necessary camber on the Separation Layer, a 3D consolidation model was completed on the TSF Upper Deposit to assess the void ratio profile and average dry density of the material driving the consolidation of the Lower Deposit. The predicted average dry density was used to estimate the combined uniform surcharge pressure exerted on the Lower Deposit by the overlying rockfill Separation Layer and the Upper Deposit. Next, several 1D consolidation models were completed under the anticipated combined uniform surcharge pressure to predict differential settlements of the geomembrane liner system due to the compressibility of the unlined Lower Deposit. These analyses were used to design the necessary camber on the Separation Layer to mitigate damage to the geomembrane liner system of the Upper Deposit and to maintain gravity flow across the Separation Layer (below the hydraulic sink elevation) to perimeter collection sumps. Finally, the modeling results were combined to estimate the anticipated dry density of the tailings at the end of filling of the overall TSF.

1 INTRODUCTION

Large volumes of tailings are generated worldwide as a result of mining. Conventionally, these mine tailings are stored by constructing cross-valley embankments or perimeter dikes with the help of waste rock and/or naturally occurring fill material readily available nearby. However, as mine sites age, a shortage of suitable locations for safe and economic disposal of mine tailings often presents itself, with mine operators looking for new and innovative alternatives. In recent years, in-pit Tailings Storage Facilities (TSFs) have garnered attention as one viable alternative. As the name suggests, these are storage facilities where an historic open pit is backfilled with mine tailings. This method is attractive to mine operators as open pits can often be filled at a fraction of the costs associated with designing, constructing, and operating a conventional TSF. In addition, pit walls eliminate the need for perimeter dikes, and thus the risk associated with embankment instability is greatly reduced or eliminated (EPA, 1994). However, there are also many potential risks associated with in-pit TSFs such as potential for groundwater contamination near the pit, poor consolidation characteristics of the tailings deposited within the pit and potential hazards associated with it, and reduced rework potential of the backfilled pit.

As with design of any TSF, estimating storage capacity of the TSF is essential part of the process, which is dependent on the consolidation behavior of material under self-weight and the rate of rise of the tailings during deposition. As a result of advancements in the understanding of large-strain consolidation characteristics of tailings slurries, this can be accomplished to a relatively high degree of accuracy by combination of laboratory Seepage Induced Consolidation (SIC) tests and computer-based consolidation models. Specialized applications of consolidation modeling can also be used in other steps of the design process in addition to estimating tailings storage capacity. The planned in-pit TSF discussed herein is unique because it utilizes a combination of three-dimensional (3D) and one-dimensional (1D) consolidation models during design of an open pit TSF due to the hydrogeology of the area and envisioned complexities of the tailings deposit development within the open pit.

The planned development of this in-pit TSF is envisioned to consist of a layered system, which includes: 1) the Lower Deposit, 2) the Separation Layer, and 3) The Upper Deposit. The Lower Deposit is planned to be unlined because the hydrogeology of the area provides a hydraulic sink toward the pit and the groundwater is maintained below a certain level by continuous pumping, which mitigates the potential for groundwater contamination. The Upper Deposit is located above the hydraulic sink elevation and will require a geomembrane liner system to prevent contamination of groundwater sink. The Lower Deposit is designed to be below approximately elevation 3340 meters above sea level (masl). Subaqueous tailings deposition will be used for the Lower Deposit and a water cover will be maintained to keep the tailings submerged. A separation layer is envisioned to be constructed between the Lower Deposit and Upper Deposit to provide a drain layer and buffer/monitoring zone such that local groundwater levels are maintained below the 3350 masl hydraulic sink level. For this, a Separation Layer Pumping System is planned to be installed. In addition, the Separation layer will provide the foundation for the Upper Deposit.

The Upper Deposit will be constructed as a fully lined basin with the geomembrane liner system installed atop the separation layer and along a ring embankment constructed in approximately three, 30 meter lifts. The ring embankment will be supported at its base by the Separation Layer. The tailings deposited within the Upper Deposit are envisioned to span from approximately 3350 to 3438 masl (3440 masl ultimate crest elevation) for a maximum thickness of 88m. Figure 1 shows a conceptual schematic of the planned development of the tailing deposits and rockfill separation layer within the pit.

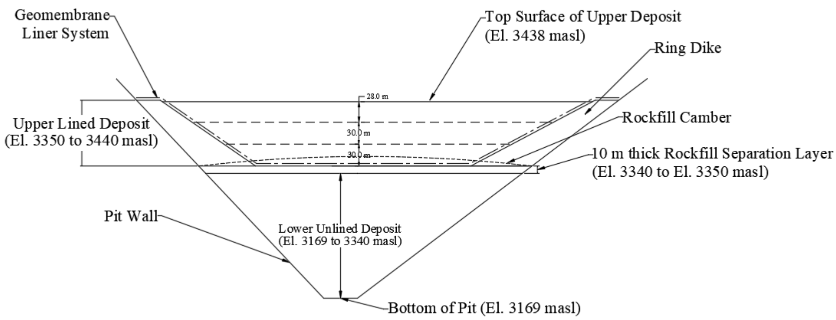

Figure 1. Planned Development of Tailing Deposits and Rockfill Separation Layer within Pit

The main objective of this paper is to illustrate the use of consolidation modeling to: 1) design the necessary camber for the Separation Layer to mitigate damage to the Upper Deposit geomembrane liner system and to maintain gravity flow across the Separation Layer (below the hydraulic sink elevation) to perimeter collection sumps, and 2) estimate anticipated dry density of the tailings within the TSF at the end of filling for the purpose of providing an estimate of the total storage capacity of the TSF.

2 TAILINGS MATERIAL PROPERTIES AND DEPOSITION RATE

The tailings material to be deposited into the proposed in-pit TSF will be mix of Flotation and Cyanide Leach Tailings denoted as “Mixed Tailings”. The laboratory testing performed on the Mixed Tailings material included index property tests such as particle size analysis with hydrometer, specific gravity testing, and Atterberg’s limit test. Based on results of these laboratory tests, the Mixed Tailings classify as non-plastic Silt with Sand (ML) according to USCS classification. Additionally, relationships between void ratio and effective stress, and between void ratio and saturated hydraulic conductivity, were evaluated using Seepage Induced Consolidation (SIC) testing. Figures 2 and 3 provide graphical representations of these relationships for the Mixed Tailings.

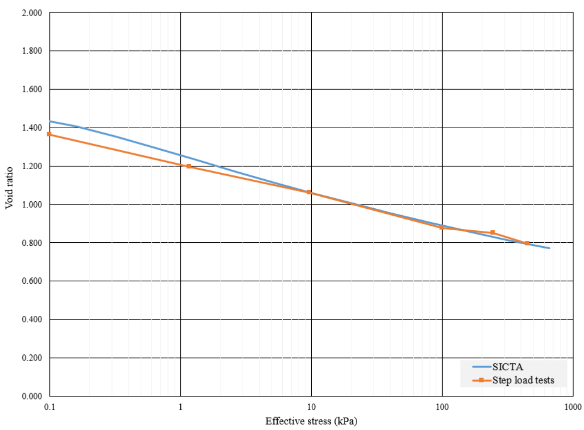

Figure 2. Variation of Void Ratio with Effective Stress from SICTA for the Mixed Tailings

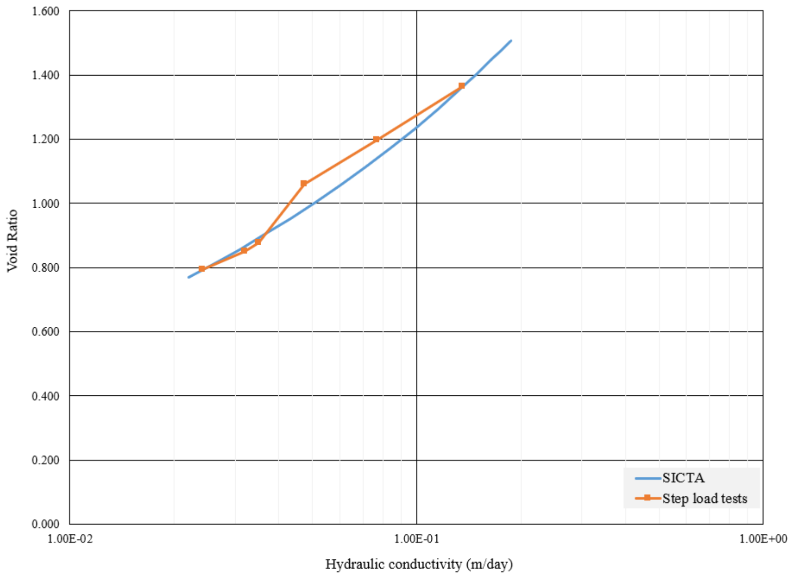

Figure 3. Variation of Void Ratio with Hydraulic Conductivity (m/day) for the Mixed Tailings

The above graphical relationships are represented by the following functions:

Compressibility: $e = A(\sigma' + Z)^B$ (1)
Hydraulic Conductivity: $k = C\, e^D$ (2)

Where: e= void ratio
k=hydraulic conductivity
σ'=vertical effective stress
A, B, C, D, and Z =curve-fit parameters (A, Z, and C depend on the system of units, and are provided herein for SI units)

The compressibility function (1) was formulated by Liu and Znidarcic (1991); whereas the permeability function was developed by Somogyi (1979). Table 1 presents the SIC testing curve-fit parameters for the tested Mixed Tailings. Table 2 presents the summary of relevant index and geotechnical engineering properties associated with the Mixed Tailings.

Table 1. Testing Results – SIC Testing Curve-Fit Parameters

Curve-Fit Parameter	Mixed Tailings
A	1.26
B	-0.076
Z (kPa)	0.09
C (m/d)	5.06×10^{-2}
D	3.19

Table 2. Testing Results – Mixed Tailings Material Properties

Material Property	Mixed Tailings
USCS Classification	Silt with sand (ML)
Gravel (%)	0.0
Sand (%)	28.7
Fines (%)	71.3
Liquid Limit (LL)	Non-Plastic
Plastic Limit (PL)	Non-Plastic
Specific Gravity	2.742
Void Ratio at Zero Effective Stress (e_0)	1.519
SIC Dry Density	1.16 – 1.46 t/m^3 over an effective over stress range of 0-100 kPa
Saturated Hydraulic Conductivity	1.56 x 10^{-4} – 4.06 x 10^{-5} cm/sec over the stress range of 0-100 kPa

The mine plans to deposit Mixed Tailings into the TSF at a deposition rate of approximately 7.37 million tons per year (Mt/y) starting from year 2027 through approximately 2039. Figures 4 and 5 show the volumetric filling curves for the Lower Deposit and Upper Deposit, respectively.

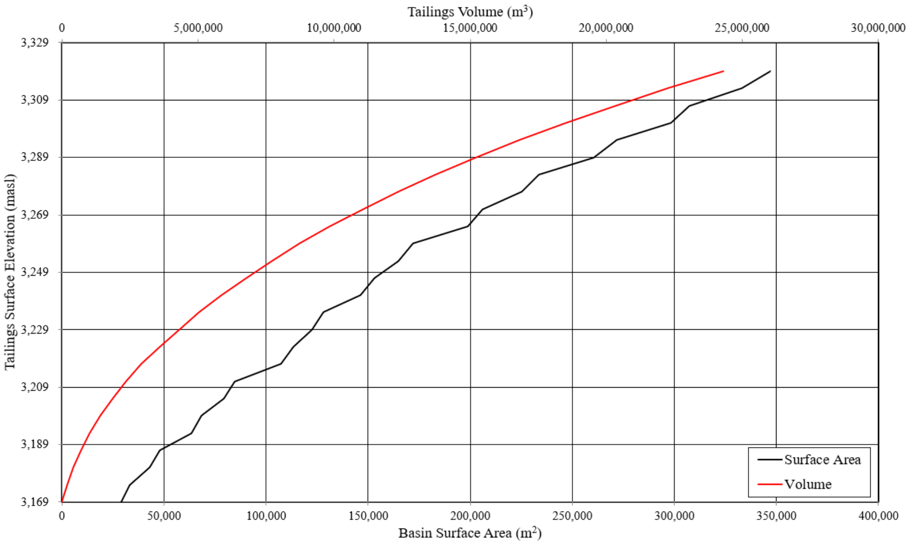

Figure 4. TSF Filling Curve – Lower Deposit

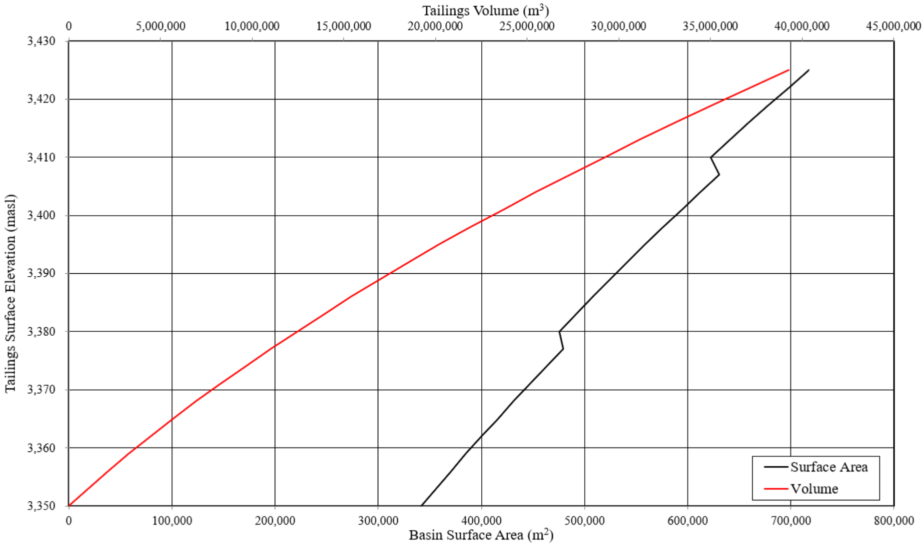

Figure 5. TSF Filling Curve – Upper Deposit

3 CONSOLIDATION MODELING

3.1 *Consolidation modeling software*

Consolidation modeling was performed using the results from the laboratory testing described above and the modeling algorithm described by Gjerapic and Znidarcic (2007), which was implemented into the CONDES consolidation software developed at the University of Colorado Boulder. CONDES is a finite-difference program which solves the non-linear, partial differential equation proposed by Gibson et al (1967) as shown below, which describes 1D consolidation.

$$\pm\left(\frac{\rho_s}{\rho_f}-1\right)\frac{d}{de}\left[\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z}+\frac{\partial}{\partial z}\left[\frac{k(e)}{\rho_f(1+e)}\frac{d\sigma\prime}{de}\frac{\partial e}{\partial z}\right]+\frac{\partial e}{\partial t}=0 \tag{3}$$

Where ρ_s is the unit weight of solids, ρ_f is the unit weight of fluid, *k(e)* is the coefficient of hydraulic conductivity as a function of the void ratio e, and z is the height of solids from a specified datum. The Gibson equation (Gibson et al, 1967) allows for non-linear, stress-dependent representations of the void ratio-effective stress and void ratio-hydraulic conductivity relationships without restriction on the shape of these functions. The CONDES software provides a numerical solution to the consolidation equation. This solution is combined with the planned tailings production and the geometry of the impounding TSF such that concurrent deposition and consolidation can be modelled; similar to the process expected by depositing slurry tailings into the TSF. The filling scheme is such that the model accounts for the three-dimensionality of the impoundment for a more accurate estimate of the average dry density developed within the TSF. Both 1D and 3D versions of the CONDES software are available, and both were used for different aspects of this project. The 3D version was used to model consolidation during filling, while the 1D version was used in various locations to understand the potential for differential settlement of the separation layer.

3.2 *Modeling Assumptions and Simplifications*

The following assumptions were made in developing the consolidation modeling presented herein.

1. The in-pit TSF will be developed as two separate deposits (Lower Deposit and Upper Deposit). Beach slopes will be developed during the filling of both the Upper and Lower Deposits to their respective maximum average tailings elevation. It is assumed these developed beach slopes will not significantly impact the results of the consolidation modeling.
2. The Upper and Lower Deposits will attain two different average dry densities at the end of consolidation due to the presence of the Separation Layer, the Upper Deposit being geomembrane lined, and differing effective stress regimes acting upon each deposit; therefore, separate consolidation models were performed for the Lower Deposit and the Upper Deposit.
3. Additional differential consolidation settlement is expected to occur within the Lower Deposit due to the surcharge load developed by the Separation Layer and the development of the Upper Deposit above the separation layer. This was accounted for in the overall assessment through the completion of several 1D consolidation models using the 1D version of CONDES. The surcharge pressure applied to each of the 1D models was estimated and uniformly distributed over the top surface of the Lower Deposit. The immediate embedment of the Separation Layer into the Lower Deposit that will develop due undrained shearing during construction of the Separation Layer over the soft tailings in the Lower Deposit was not incorporated as a part of consolidation modeling exercise, and is not expected to significantly impact the results estimated herein.
4. An average production rate of 20,180 tons per day (tpd) was assumed based on the average of the planned deposition rates for years 2027 through 2039 (~7.37 Mt/y).
5. Segregation of the material is anticipated to be limited and the tailings will be sufficiently homogeneous such that a single set of material properties is representative of the new Mixed Tailings to be deposited into the TSF.
6. The planned Mixed Tailings will contain high concentrations of gypsum. It is anticipated the gypsum will create a binding effect along the unlined pit wall boundary within the Lower Deposit to promote minimal bottom drainage, thus a no-flow bottom boundary was assumed for consolidation modeling of the Lower Deposit. The Upper Deposit is planned to be a geomembrane lined; therefore, a no-flow bottom boundary was also adopted for consolidation modeling on the Upper Deposit.
7. The supernatant fluid was assumed to be water.

3.3 *Consolidation Modeling Approach*

Since the lifecycle of this In-pit TSF involves recurring periods of construction and deposition, and continuous monitoring of groundwater, it is necessary for the modeling approach to consider the major consolidation processes during the time period. The approach discussed herein effectively captures the following processes:

- Concurrent deposition and self-weight consolidation of the Lower Deposit.
- Simultaneous consolidation of the Lower Deposit due to development of the overlying Separation Layer and Upper Deposit.
- Concurrent deposition and self-weight consolidation of the Upper Deposit.

The modeling does not account for embedment of the rockfill Separation Layer due to undrained shearing that would occur during its placement onto the deposited tailings at the surface of the Lower Deposit. This process has been handled separately outside of the scope of this paper.

During tailings deposition within the Lower Deposit (from elevation 3169 to 3340 masl), concurrent self-weight consolidation of the tailings will occur. To assess the anticipated void ratio distribution within this portion of the deposit at the end of the deposition, a 3D consolidation model was completed. During filling, surface (surcharge) loading and evaporation were assumed to be zero due to the sub-aqueous deposition plan. The results of this modeling were used to estimate the average dry density of the tailings over time and to estimate the expected time needed to fill the unlined lower portion of the pit to an average tailings elevation 3340 masl.

The role of Separation Layer overtop the Lower Deposit is to maintain the ground water level below the elevation of the hydraulic sink. An additional function of the separation layer is to mitigate potential groundwater contamination above the hydraulic sink level by providing a competent foundation for the Upper Deposit geomembrane liner system and opportunity for seepage collection from both the Upper (downward seepage) and Lower Deposits (upward drainage during consolidation). As such, the separation layer needs to be carefully designed such that there will be no damage to the geomembrane liner system overtime due to continued consolidation-settlement of the Lower Deposit and the Separation Layer due to self-weight and filling of the Upper Deposit.

To model this deformation and design the necessary camber on the Separation Layer to prevent damage to the geomembrane liner system, a 3D consolidation model was completed on the Upper Deposit (from elevation 3350 to 3438 masl) to assess the void ratio profile and average dry density of the surcharge material driving additional consolidation of the Lower Deposit. As before, surface loading and evaporation were assumed to be zero. The predicted average dry density of the Upper Deposit was used to estimate the combined uniform surcharge pressure exerted on the Lower Deposit tailings by the overlying rockfill Separation Layer and the Upper Deposit. Next, several 1D consolidation models were completed under the anticipated combined surcharged pressure to predict differential settlements of the geomembrane liner system due to the compressibility of the unlined Lower Deposit (i.e., settlement of the top surface of the Lower Deposit).

After completion of the 3D and 1D consolidation models, the maximum time rate of consolidation from 1D consolidation models was compared against the total time required for simultaneous filling and self-weight consolidation of Upper Deposit to confirm that the consolidation-settlement under surcharge is generally completed before the end of Upper Deposit deposition (limited long-term additional consolidation of the Lower Deposit post-operations). Meeting this criterion was a crucial part of modeling for closure design consideration of the TSF. The results of these analyses were used to design the necessary camber on the Separation Layer to mitigate damage to the geomembrane liner system of the Upper Deposit and to maintain gravity flow across the Separation Layer (below the hydraulic sink elevation) to perimeter collection sumps.

3.4 *Consolidation Modeling Results*

Figures 6 and 7 provide a variation of tailings surface elevation and average dry density over time for filling and self-weight consolidation within the Lower Deposit and Upper Deposit, respectively. The key findings from the modeling such as average dry density, approximate time to filling, and estimated total storage tonnages are presented in Table 3.

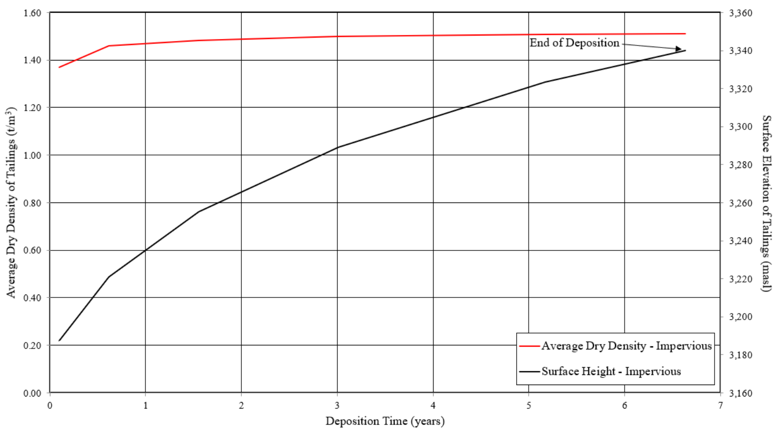

Figure 6. Lower Deposit - Tailings Surface Elevation & Average Dry Density over Time

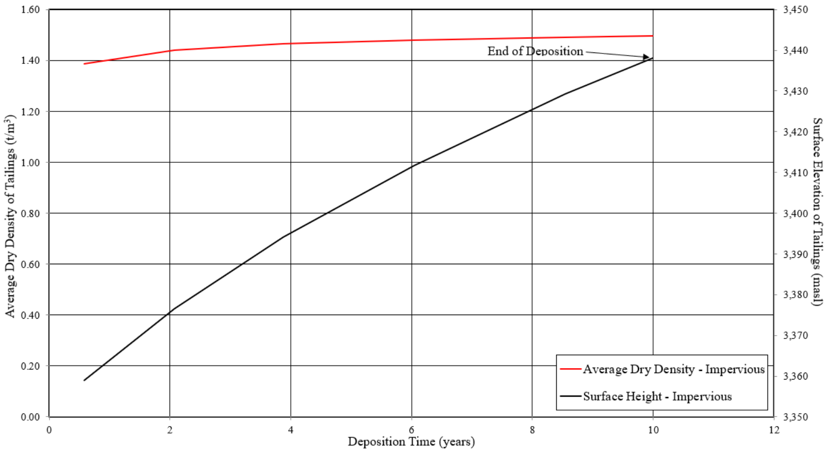

Figure 7. Upper Deposit-Tailings Surface Elevation & Average Dry Density over Time

Table 3. Summary – Self-Weight Consolidation Modeling Results

In-Pit TSF Deposit	Bottom Boundary Condition	Average Dry Density (t/m^3)	Approximate Time to Fill (years)	Estimated Total Storage (Mt)
Lower Deposit (unlined)	Impervious	1.51	6.6	48.5
Upper Deposit (lined)	Impervious	1.50	9.9	72.7

Figures 8 and 9 provide dry density profiles for the in-situ tailings at the thickest points for the Lower Deposit and Upper Deposit, respectively. As seen on Figures 8 and 9, the density profiles are relatively parallel throughout the TSF development. Thus, it can be qualitatively assessed that the materials will be approximately normally consolidated under self-weight loading during filling. This means that minimal excess (i.e. above hydrostatic) pore pressure is expected within the tailings and limited long-term settlement is expected to occur due to self-weight loading. Therefore, for the Upper Deposit, significant additional consolidation is not expected without additional applied loading or reduction in phreatic surface after deposition is completed within the TSF. However, since the Lower Deposit will experience surcharge loading due the overlying Separation Layer and development of the Upper Deposit, the tailings within the Lower Deposit will undergo further settlement after filling of that portion of the deposit. This was accounted for by completing six 1D consolidation models. These six models represent six concentric annuli of varying height which collectively form the simplified 3D geometry of Lower Deposit impoundment used in the 3D consolidation modeling. The central annulus was the tallest, and the height of each annuli decreased moving outward with the pit walls. As a result, six height vs void ratio profiles were developed. These models were run with an estimated surcharge pressure of 1875 kPa uniformly distributed over the top surface of the Lower Deposit which was calculated considering the average saturated unit weight of Upper Deposit Mixed Tailings (19 kN/m^3) over a depth of 98m (10 m thickness of rockfill plus 88 m depth of tailings within the Upper Deposit from 3350 to 3438 masl). The dry unit weight of the Separation Layer rockfill was assumed to be the same as the saturated unit weight of the Upper Deposit Mixed Tailings to simplify the modeling approach. Table 4 presents the results of 1D consolidation models completed.

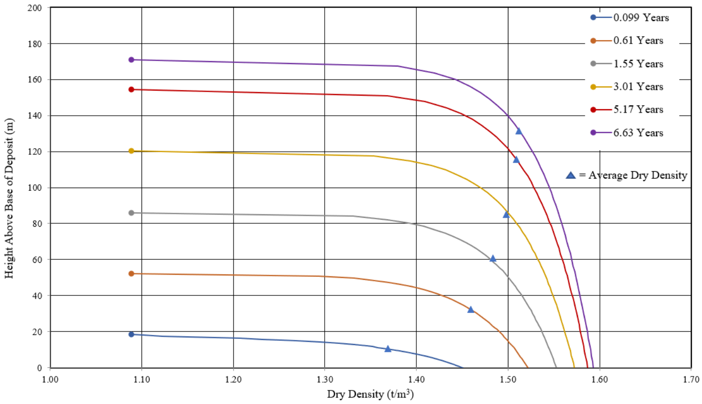

Figure 8. Lower Deposit – Tailings Dry Density Profile – Mixed Tailings

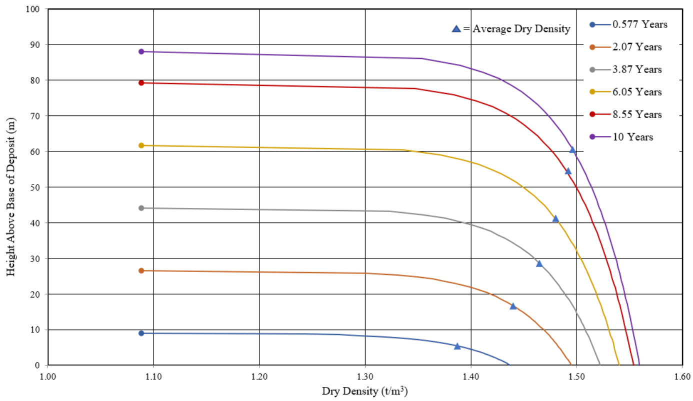

Figure 9. Upper Deposit – Tailings Dry Density Profile – Mixed Tailings

Table 4. Summary – Surcharge Consolidation Modeling Results

Annulus ID	Annulus Surface Area (m^2)	Annulus Height after Self-Weight Consolidation (m)	Annulus Final Height (m)	Total Settlement (m)	Approximate Time for Consolidation (days)
1	120,352	16.7	14.7	2.0	19
2	97,611	50.8	46.5	4.3	139
3	72,569	84.9	79.0	5.9	334
4	59,385	118.9	111.7	7.2	579
5	46,926	152.6	144.2	8.5	858
6	29,160	171.0	162.1	8.9	1022

The Annuli (numbered 1 through 6) represent the top surface area of the Lower Deposit, with Annulus 1 being the outermost shell and shallowest portion of the deposit, and Annulus 6 being the central "column" and deepest portion of the deposit. Annuli 2 through 5 represent the intermediate portions of the deposit between Annuli 1 and 6. As shown in the table, the outermost annulus (Annulus 1) experiences the least settlement due to the lower thickness of the Lower Deposit along the edge of the TSF. The annulus settlements increase moving inward toward the deeper/thicker portions of the deposit. The central annulus (Annulus 6) experiences the maximum settlement of roughly 8.9 m over 1,022 days (~2.8 years). As seen in Table 3 above, it is estimated that the Upper Deposit will be filled and consolidated under its own weight in approximately 9.9 years. Therefore, the Lower Deposit surcharge load consolidation will be achieved concurrently with the filling and self-weight consolidation of the Upper Deposit, and long-term settlement of the Lower Deposit due to the surcharge load is not anticipated after deposition within the Upper Deposit ceases.

The Separation Layer was designed with camber to accommodate the differential settlements shown in Table 4 with appropriate factors of safety implemented to account for variability from modeled settlement values. As the Upper Deposit is developed, the Lower Deposit tailings will continue to experience the consolidation settlement which will be balanced by the proposed camber based on the settlement values provided in Table 4 such that when consolidation is completed, the floor of Upper Deposit (at the location of the geomembrane liner system) remains slightly cambered such that the settlement beyond a level configuration will not impart excessive strain on the Upper Deposit geomembrane liner system.

4 CONCLUSION

The tailings deposited into the in-pit TSF described in this paper was modeled using a combination of 1D and 3D large-strain consolidation models to estimate the anticipated dry density of the tailings in the Upper and Lower deposits at the end of filling and to design necessary camber on the proposed rockfill Separation Layer between the two deposits to prevent excessive strains in the proposed geomembrane liner system which will be constructed between the two deposits. This work was completed using the consolidation modeling software, CONDES, developed at the University of Colorado at Boulder. The input parameters were developed with the use of seepage induced consolidation testing (SICT) performed on the proposed Mixed Tailings which will be deposited into the facility. While estimating storage capacity using large-strain consolidation models is common during design and management of tailings storage facilities, additional applications of these types of models can further aid in the understanding of and help to provide solutions to additional challenges identified during design and development of these facilities as illustrated by the work completed and presented herein.

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