Thickened tailings deposition modeling using a large strain consolidation model

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Michaël Demers Bonin & Anne-Marie Dagenais
Golder Associés Ltée, Montréal, Qc, Canada
Mathieu Nuth & Alexandre R. Cabral
Department of Civil Engineering – Université de Sherbrooke, Sherbrooke, Qc, Canada

ABSTRACT
The use of thickened tailings (TT) has increased over the last forty years due to the perceived benefits of using this technology for tailings disposal. Observations from self-weight consolidation tests performed in settling columns on gold mine tailings indicated that thickened tailings at higher solids content typically exhibit self-weight consolidation behavior only. Based on this observation, the CS2 code was used to model the experimental consolidation behavior of thickened tailings observed in settling columns. The results from CS2 were conclusive and lead to further modeling tailings deposition on a large scale using the CS4 1D code, which shares the same formulation as CS2 but considers layer accretion, rather than instantaneous filling. The numerical formulation of the two codes accounts for large strain and variable compressibility and hydraulic conductivity during the consolidation process.

RÉSUMÉ
L'utilisation des résidus épaissis a connu une hausse ces 40 dernières années en partie en raison des bénéfices environnementaux qu'on leur attribue. À l'aide d'essais de consolidation en colonne de tassement, il a été démontré que dans le haut de la gamme des % solides reliés aux résidus épaissis d'une mine aurifère, le matériel subit principalement une déformation en consolidation sous son propre poids lors de la déposition. Suivant cette observation, le logiciel CS2 a été utilisé pour reproduire le comportement en consolidation sous le poids propre de résidus épaissis observé en colonne de tassement. La qualité des reproductions numériques des résultats expérimentaux obtenus de CS2 a incité à étendre l'étude du comportement en consolidation à une déposition progressive 1D à grande échelle à l'aide du logiciel CS4, lequel est basé sur la même plateforme de calcul que CS2 (grande déformation, compressibilité et conductivité hydraulique variables), mais permet en plus la modélisation d'un dépôt dont la hauteur augmente progressivement dans le temps.

1 INTRODUCTION

1.1 General considerations and review of self-weight consolidation

The use of thickened tailings (TT) has increased over the last forty years due to the perceived benefits of using this technology for tailings disposal. Amongst the benefits attributed to TT are the possibility to form a self-supporting stack and the decrease in bleed water released in the tailings storage facility.

Self-weight consolidation is a coupled hydro mechanical process that greatly influences the storage capacity of tailings disposal facilities and therefore needs to be well understood.

Figure 1 presents a typical settlement curve of slurry placed at an initial void ratio ($e_0<e_m$), where e_m is the soil formation void ratio. At e_m, slurry undergoes self-weight consolidation only. At the very beginning of the process, the particles are in suspension in a dense fluid medium. Self-weight consolidation begins as soon as the solid particles build a skeleton whereby soil particles transmit their weight to the bottom (following time t0 in Figure.1) (Been and Sills 1981), while dissipation of u_e occurs simultaneously with settlement. The driving mechanism is the dissipation of u_e, which is caused by the buoyant unit weight of the soil particles. When self-weight consolidation starts, the effective stress builds up and the slurry starts to behave as a soil. Self-weight consolidation is over when the soil stratum is in equilibrium under its own weight (time t4 in Figure 1).

This paper focuses on self-weight consolidation only. Nonetheless, it is recognized that slurry deposited at high enough void ratio will first exhibit sedimentation before reaching e_m that marks the transition toward an effective stress dependent behavior. Several works present the interaction of sedimentation and self-weight consolidation through experimental and/or numerical studies (Imai 1981, Pane and Schiffman 1985, Li and Williams 1995, Jeeravipoolvarn et al. 2009).

In turn, benchmark studies enabled a better understanding of self-weight consolidation underwent by slurries (Gibson et al. 1981, Imai 1981, Sills 1998).

Observations from settling columns experiments performed on gold mine tailings indicated that TT at higher solids content (or low enough void ratio) typically exhibit self-weight consolidation only depending on the initial deposition void ratio (Demers Bonin et al. 2014).

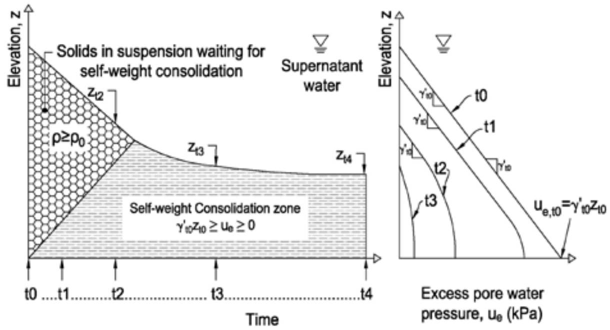

Figure 1. Typical settlement curve and profiles of excess pore water pressure (u_e) of slurry undergoing self-weight consolidation with upward drainage only and without flocculation, adapted from (Imai 1981)

1.2 Modeling of self-weight consolidation

Several studies present numerical tools that have been developed over the last decades to model self-weight consolidation (Seneviratne et al. 1996, Fox and Berles 1997, Yao and Znidarcic 1997, Burger and Concha 1998, Bartholomeeusen et al. 2002, Jeeravipoolvarn et al. 2009). Such modeling tools account for large strains, variable hydraulic conductivity and compressibility. The deposition is modeled as instantaneous or progressive and evaporation effects are sometimes featured.

1.3 Scope of the study

The presented study provides relevant information for tailings management, from the viewpoint of large-strain consolidation at the early stages of deposition and settlement. The paper provides a procedure for using settling column test results and contributes to furthering the knowledge gained from such experiments, when they are coupled to large strain models as CS2 and CS4.

The compressibility and hydraulic conductivity relationships are calibrated with CS2 for settling columns experiments in which TT from a gold mine were deposited. The calibrated constitutive relationships were then used to model a large scale 1D progressive deposition with CS4. The modeled excess pore water dissipation (u_e) and deformation were examined in the simulations. The influence of the selected constitutive relationships was also the object of a parametric study.

2 MATERIALS AND METHODS

2.1 Materials

The gold tailings samples were shipped from a Canadian mine in 20 L sealed pails. Upon arrival, the tailings were highly consolidated at the bottom of the pails with supernatant water on top. The gravimetric water content (w) was about 34.7% after having settled during transport. The gravimetric water content was about 50.7% after being homogenized with the supernatant of the sample. It is common practice in the mining industry to evaluate the solids concentration in terms of solids content which is the mass of dry solids divided by the total mass of tailings. In this case, the material was studied at 68% solids (e_0=1.29) and 72% solids (e_0=1.07). Typically, the solids content of TT range between 50% and 70%, but experiments were conducted at 72% in this study to collect data over a broader range. Tailings have been dried and then homogenized with distilled water and prepared to the target solids content or void ratio. The type of water used for the deposition tests (distilled or from the site) had no influence on the self-weight consolidation.

The mine tailings studied in this project correspond to a silt-sized material with a low plasticity as it is often reported for gold tailings (Bussière 2007). Table 1 summarizes geotechnical characteristics of the studied tailings. The soil formation void ratio was estimated between 1.30 and 1.45 as evidenced by settlement curves and pore water pressure dissipation responses from settling column experiments initiated at various void ratios between 1.07 and 2.89.

Table 1. Characteristics of tested tailings

Characteristics	Gold tailings
Gs	2.76 to 2.77
W_L (%)[1]	29
W_P (%)	25
I_P (%)	4
Sand >75µm (%)	8
Silt (%)	81
Clay sized particles<2µm (%)	11
D_{10} (mm)	0.0018
D_{60} (mm)	0.021
C_U	12
USCS classification	ML
e_m (soil formation void ratio)[2]	1.30-1.45

[1]Determined with the Swedish cone method
[2]Determined from settling columns experiments initiated at various initial void ratios

2.2 Experimental setup and method

Self-weight consolidation experiments were conducted in a settling column shown in Figure 2. The 300 mm-high settling column was made of clear acrylic with an internal diameter of 101.6 mm. Total pore water pressure was monitored at three elevations (bottom, 0.1 m and 0.2 m) for the 68% samples. Thereafter, an additional pressure transmitter was added at 0.05 m for the 72% samples in order to increase resolution in the lower section of the column. Pressure transmitters (LMP 331, BD Sensors, Thierstein, Germany; range of 0 to 10 kPa, accuracy of ±0.01 kPa) were attached to the column wall.

The tailings-water interface settlement of the 72% samples was recorded automatically with a digital camera focused on a paper-thin measuring scale fixed to the interior wall of the column as used by Pedroni (2011). Care was taken to ensure that the digital camera followed the tailings-water interface down. After completion of self-weight consolidation (i.e. once u_e was completely dissipated), the final tailings height (H_f) was recorded and the supernatant water was weighed. u_e was calculated by subtracting the hydrostatic pressure (u_h) from the total pore water pressure (u) measured.

The experimental procedure is described in details by Demers Bonin et al. (2013, 2014).

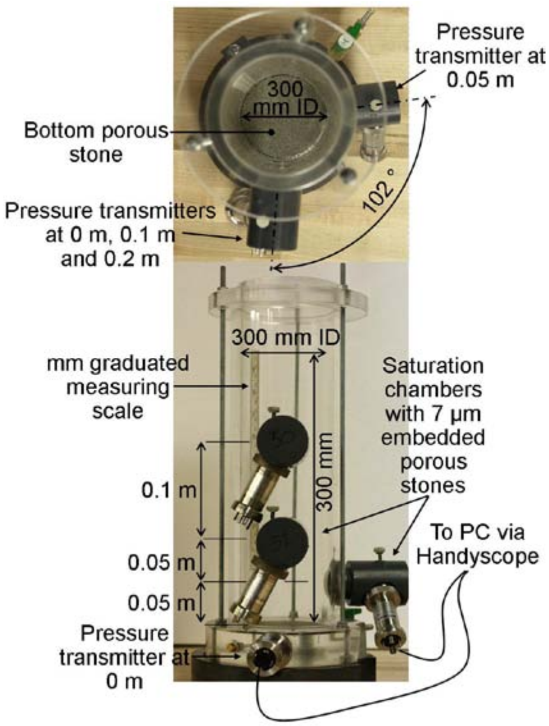

Figure 2. Settling column equipped with four pressure transmitters. Handyscope is an interface device for data logging.

2.3 Validation of CS2 and CS4 numerical models

CS2 (Fox and Berles 1997, Pu and Fox 2012) was first used to calibrate constitutive relationships based on experimental results from settling columns. The compressibility and the hydraulic conductivity relationships were adjusted to provide the best-fit with reference to experimental pore water pressure dissipation responses, settlement or final void ratio profiles as explained by Demers Bonin et al. (2014). This method ensures that both pore pressure and mechanical aspects are accounted for. Once the relationships were determined, they were used in a subsequent 1D progressive deposition modelling using CS4.

CS4 (Fox 2000) is a large strain consolidation model based on a very similar numerical formulation to that of CS2. It was built on a piecewise-linear method that includes a Lagrangian approach, which follows the motion of the solid phase during the consolidation process. Moreover, CS4 has the facility to model the accretion of layers.

Both CS2 and CS4 were implemented in Matlab and verified with the original code based on the corresponding examples provided by Fox and Berles (1997) and Fox (2000).

The comparison between CS4 and CONDESO (Yao and Znidarcic 1997) provided herein shows the consistency of our approach with the well-known code CONDESO, which also takes progressive deposition into account, and that has been used more intensively by the industry. For this purpose, data from Example 2 in Yao and Znidarcic (1997) were reproduced in Figure 3. Modeling parameters (constitutive relationships, initial void ratio and specific gravity) are provided in Figure 3a. The 1D column was divided in 100 elements in CS4 whereas the CONDESO column had 51 nodes. Note that CS4 gives the void ratio at the centroid of each element, whereas CONDESO provides the void ratio at the nodes. This explains the slight discrepancy at the top of the void ratio profile. In fact, the final CS4 void ratio profile (Figure 3a) should be higher by a value equal to $0.5h(R_s)$, where $h(R_s)$ is the height of the 100th element in this case.

Figure 3a first presents the prediction of the final void ratio profile, while Figure 3b presents the evolution of height with time. The near-perfect agreement obtained in both cases validates the capabilities of CS4 with reference to a well-known code that is based on the resolution of the Gibson et al. (1967) equations. The results suggest that CS4 is based on a reliable numerical formulation to estimate deformations of an accreting thickened tailings layer.

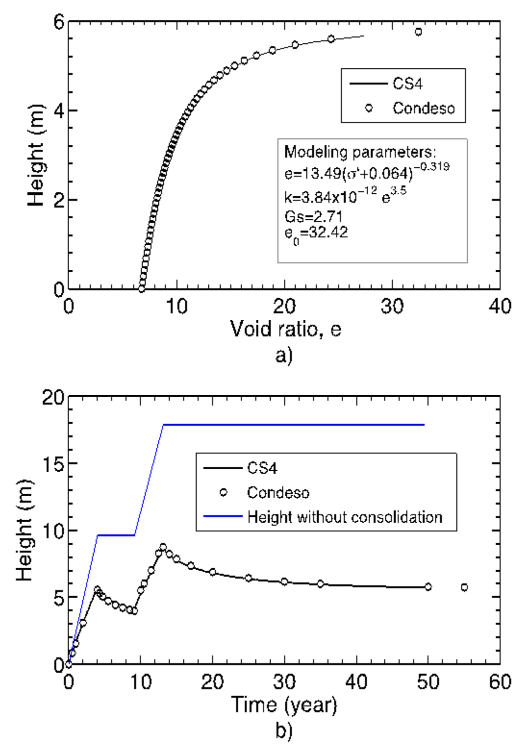

Figure 3. a) Void ratio profile; b) height versus time obtained from CONDESO and CS4 for example 2 from Yao and Znidarcic (1997)

3 RESULTS

3.1 Results from settling column and calibration of constitutive relationships

Two series of tests (68% and 72% solids) are used herein to illustrate the calibration procedure that was carried out. Table 2 presents a summary of the results from those tests.

Table 2. Summary of self-weight consolidation results from settling columns

Test ID	H_0 (m)	Initial solids content (%)	Initial void ratio, e_0	H_f (m)	Vertical strain (%)
68%[1]	0.300	68.21	1.29	0.265	11.7
72%[2]	0.301	72.09	1.07	0.281	6.7

[1] Average values based on four nearly similar tests taken from (Demers Bonin et al. 2014).
[2] Data from one single test performed at 72% solids.

Experimental results were calibrated using CS2. Constitutive relationships were adjusted to provide the best-fit match between CS2 simulations results and experimental results. The CS2 columns were divided in 50 vertical elements (R_j=50). Experimental void ratios and initial heights were used as input within CS2 for the 68% and the 72% simulations. The retained calibrated relationships resulted in initial effective stress q_0 of 0.0083 and 0.1019 kPa and initial hydraulic conductivities (k_{qo}) of 8.11x10^{-7} and 5.99x10^{-7} m/s, respectively for the 68% and 72% simulations. 51 discrete data points were used in the CS2 simulations.

Figure 4 shows the calibration of the excess pore water pressure responses. Figure 4a shows the profiles of experimental excess pore water pressure results (symbols) versus the CS2 profiles (solid lines without symbol) for the 72% solids test column. In turn, Figure 4b shows the histories of excess pore water pressure versus time for experimental and simulations results at 68% solids.

Figure 4 shows that the process starts from the base of the column at the very moment of the TT deposition and moves upward with concomitant u_e dissipation. Demers Bonin et al. (2014) provided a thorough interpretation of typical self-weight consolidation through u_e results. Figure 4 shows that CS2 can reproduce closely self-weight consolidation results with reference to excess pore water pressure (u_e).

The calibration procedure was also conducted with reference to mechanical responses. Two parameters could be used as reference, i.e. void ratio profiles and settlement curves. Figure 5 shows results obtained from the calibration procedure based on the settlement curve (Figure 5a) and the final void ratio profile at 68% solids only (Figure 5b).

Figure 5a shows the settlement curve at 72% solids with several interface positions monitored with a digital camera during the entire self-weight consolidation process. Moreover, it shows the final interface position observed in the test at 68% solids at the end of self-weight consolidation. No interface position monitoring was performed for the 68% solids sample. Lines refer to the CS2 simulation with the retained constitutive parameters. Both agree well with the experimental results.

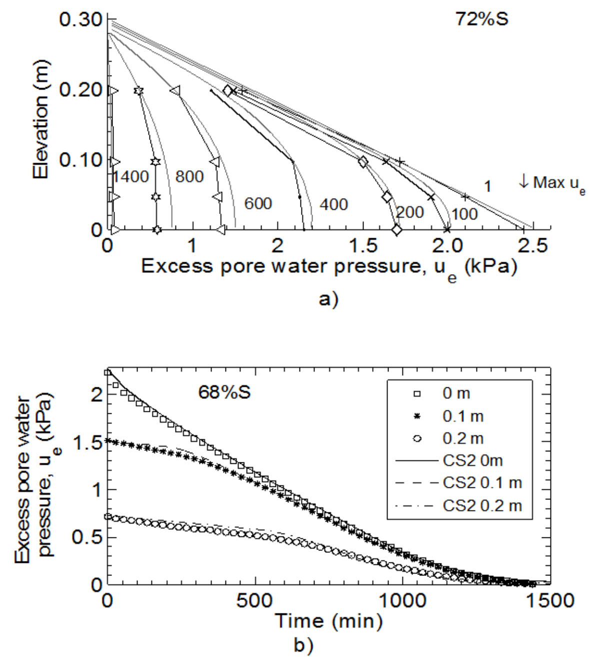

Figure 4. Calibration of constitutive relationships with reference to experimental excess pore pressure u_e expressed as profiles in (a), and histories of u_e versus time in (b). Symbols refer to experimental results while lines refer to CS2 results. Note that four pressure transmitters were used in the 72% test (a), whereas three transmitters were used in the 68% test (b).

The other method of calibration uses void ratio profiles. The final experimental void ratios were measured at bottom and at surface of the test at 68% solids at equilibrium (Figure 5b). The CS2 simulation results matches the two void ratio measurements when using the retained constitutive parameters. However, the accuracy of measurement of experimental void ratios presented in Figure 5b is less than desired because the consolidated sample had to be remoulded to measure the water content. The accuracy of void ratio could have been improved by using γ-rays density measurements. Such method has proven to be reliable in similar experiments to monitor the evolution of density over the whole process of self-weight consolidation (Been and Sills 1981, Alexis et al. 2004, Pedroni 2011).

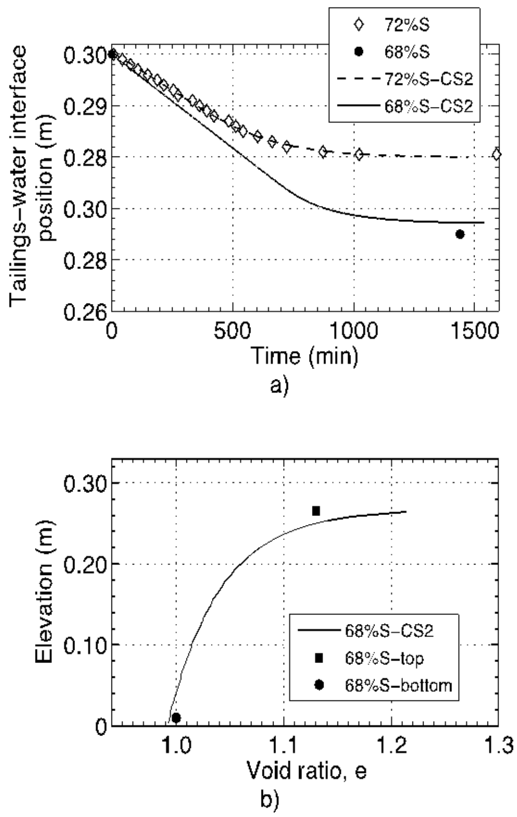

Figure 5. Calibration of constitutive relationships with reference to (a) tailings-water interface settlement, and (b) final void ratio profile for the 68% solids TT

3.2 Examination of the selected constitutive relationships

Table 3 presents the retained constitutive parameters of the 68% solids and the 72% solids tests based on the CS2 simulations that provided the best-fit match. Both constitutive relationships are plotted in Figure 6.

The use of power laws has been reported to represent fairly well both the compressibility relationship (Carrier III et al. 1983, Stone et al. 1994) and the hydraulic conductivity relationship of soft soils (Pane and Schiffman 1997, Jeeravipoolvarn et al. 2009).

However, Carrier III et al. (1983) suggested that the power law might not be suitable to represent the compressibility of soft soils at high effective stresses as this could lead to an overestimation of the settlement or unreasonably low values of void ratio.

Figure 6a compares the compressibility relationships calibrated with CS2 (68% solids and 72% solids tests) and a typical consolidation curve obtained in oedometer from the same tailings. Oedometric consolidation tests conducted on soft soils provide indeed the compression indexes at high effective stresses, as soon as self-weight effects are negligible.

The oedometer compression curve gives a compression index (Cc) of 0.068 that was calculated over the whole range of represented effective stresses. It can be observed that the slope of the oedometer curve is similar to that of the two compressibility relationships from 50 kPa of vertical effective stress. Given that the maximum effective stress reached at bottom of a consolidated 50 m-high stack of thickened tailings initially deposited at 72% solids is slightly over 400 kPa, it is reasonable to think that the use of a compressibility relationship of the form of a power law is suitable for this specific material over the range of examined effective stresses.

Table 3. Calibrated constitutive relationships for 68% and 72% thickened tailings

% solids	Compressibility ($e=A\sigma'^{B}$)	Hydraulic conductivity ($k=Ce^{D}$)
68%	$1.03\ \sigma'^{-0.047}$	$3.5\times10^{-7}e^{3.3}$
72%	$0.933\ \sigma'^{-0.06}$	$5.0\times10^{-7}e^{2.67}$

In addition, Figure 6a shows that the compressibility relationships follow approximately the same slope over the entire range of effective stresses for both solids content indeed the 72% solids relationship presents a slightly more compressible material and starts at an initial void ratio of 1.07. Figure 6a tends to confirm that consolidation tests started at lower initial void ratio result in a lower final void ratio for the same effective stress.

The retained hydraulic conductivity relationships were also plotted from the corresponding initial void ratio (Figure 6b). The overall relationships behavior suggests that the 72% solids material is slightly more permeable than the 68% solids material at a given void ratio.

However, the 300 mm-high settling columns tests showed that the 68% solids TT underwent a vertical strain of 11.7% in 1440 min, whereas the 72% solids TT experienced a vertical of 6.7% over 1400 min approximately. These observations show a certain consistency within results since the 72% solids test underwent a lower vertical strain over a rather similar period of time than the 68% solids test. The examination of the numerical hydraulic conductivities at 68% and 72% solids is presented in the next section and provides an explanation to this observation.

Despite a certain consistency within experimental results, it might be possible that channeling occurred during the 72% solids tests, resulting in a more permeable slurry. Channeling was indeed observed in other settling column experiments not related directly to this study. The effects of channeling (Vesilind and Jones 1990, Holdich and Butt 1996) are not treated in this paper, but it would have certainly affected the selection of the constitutive relationships.

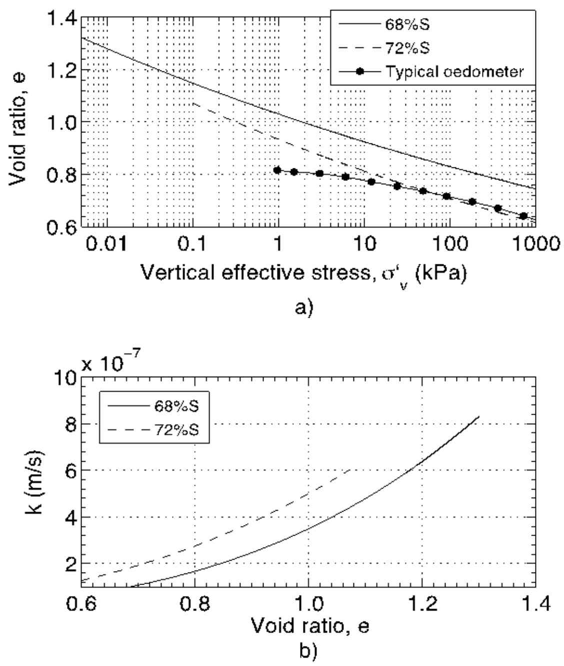

Figure 6. a) Compressibility relationships calibrated with CS2 and typical oedometer curve for the same tailings; b) hydraulic conductivity relationships fitted with the use of CS2 simulations

3.3 Progressive deposition of thickened tailings

Two 1D simulations of TT deposition at 68% and 72% solids were conducted with CS4 to evaluate the settlement and the void ratio distribution of the deposit over 15 years of deposition and 5 years of quiescent consolidation. The study of the consolidation behavior of a tailings deposition through 1D simulation proved to be adequate when the width to height ratio of the impoundment is five or less (Bromwell 1984).

The same input parameters as the ones used in CS2 were used in the CS4 simulations except for the number of discrete data points that was extended to 131. CS4 seems to be more sensitive to the amount of discrete data points defining constitutive relationships as numerical oscillations were observed in pore water pressure dissipation when a lower amount of discrete data points were used.

Figure 7 shows the location of the hypothetical CS4 1D column where vertical deformations and water flow could be expected. A 50 m-high TT stack was divided in 50 elements where upward drainage only was allowed. The bleeding water from primary and self-weight consolidation flows as runoff on the top of the CS4 column, i.e. no supernatant was allowed to accumulate in this study as it was assumed that the tailings surface is gently sloped. Otherwise, CS4 could also offer the possibility to accumulate supernatant water on top although this would not represent truly the reality as a freshly tailings layers deposited into supernatant would (sub-water deposition) normally undergo an increase in water content which could potentially affect the governing settling behaviour.

Figure 8 shows the results obtained with CS4 using the constitutive relationships calibrated with CS2 based on the 68% solids settling columns experiments. Figure 8a shows the TT deposit settlement during 15 years of operations followed by 5 years of quiescent consolidation. The blue line represents the accreting function simulated by CS4 without considering consolidation. Each tailings layer reaches equilibrium quickly following each deposition. The final height of the impoundment is approximately 39.7 m, which indicates a vertical strain of 20.6%. The insert in Figure 8a shows that the impoundment reaches equilibrium 3.5 months after the last deposition under self-weight consolidation and primary consolidation. As noted by (de Oliveira-Filho and van Zyl 2006), such gold mine tailings typically experience most of the consolidation-induced deformations during the operational period.

Figure 8b shows the void ratio profiles at 10, 14 and 20 years, the latter being the equilibrium profile. Void ratios mainly range between 0.78 and 0.97. The 14 year-profile is very similar to the 20 year-profile especially in the lower third portion of the graph. The upper part of the impoundment underwent more densification as it was more influenced by the last deposition.

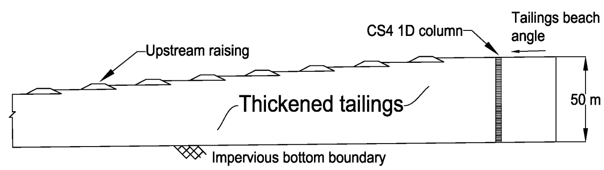

Figure 7. Typical cross-section of a thickened tailings storage facility raised by the upstream method and location of the hypothetical CS4 1D column

Figure 9 shows the same type of results but for a CS4 1D column thickened up to 72% solids. As noted earlier, this solids content is slightly higher than the typical thickened tailings solids content range (50%-70%), but it allowed explaining some additional features as evidenced by the CS4 results.

Figure 9a shows the height of tailings over time. 15 years of deposition are followed by 5 years of quiescent consolidation. The final height of the tailings impoundment is 40.82 m (vertical strain of 18.4%), which is reached approximately 4.8 months after the last deposition.

Figure 9b shows the void ratio profiles at 10, 14 and 20 years. Void ratios vary between 0.65 and 0.86. This range is lower than the result from the modeled 68% solids impoundment.

Even though the 72% solids impoundment modeled underwent slightly less vertical deformation, the comparison of Figures 8 and 9 shows that the final height of both tailings impoundments is nearly the same. The final height reached at equilibrium was 39.70 m and 40.82 m, respectively for the 68% solids and the 72% solids CS4 column. As a reference, the total height would be 50 m without consolidation. This is caused by the fact that the tailings at 72% solids were initially deposited at a lower initial void ratio thus, resulted in lower final void ratio. The final void ratio profiles vary between 0.78 and 0.97 in the case of the 68% solids model while the range decreases between 0.65 and 0.86 for the 72% solids modeled column. In both cases, most of the deformations occur during the operational period. In addition, the 72% solids TT contains more solids particles for an equivalent volume and generates higher effective stresses.

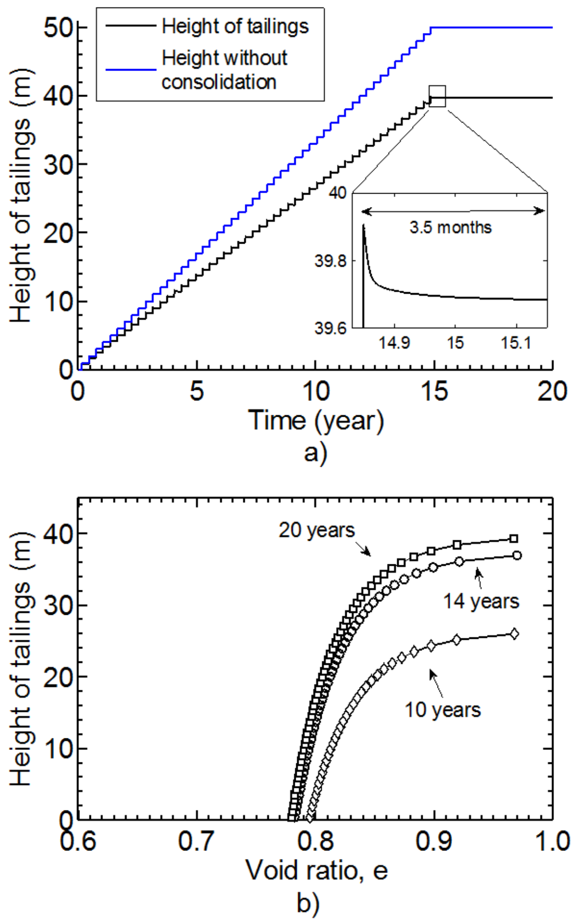

Figure 8. a) Height versus time; b) void ratio profiles at 10, 14, and 20 years for a 15 year long deposition of 68% thickened tailings followed by 5 years of quiescent consolidation

The 72% solids TT impoundment reached equilibrium slightly more slowly following the last deposition as evidenced by the inserts in Figures 8a and 9a. The 68% solids TT impoundment reaches equilibrium in 3.5 months following the last deposition whereas the 72% solids TT stack does so in 4.8 months. The first element that explains this fact is the final height of the 72% solids impoundment, which is 1.17 m higher than the 68% solids stack. This results in a slightly longer drainage path. Secondly, the examination of the hydraulic conductivitiy profiles (Figure 10) at 10 years for both impoundments show that the k_{sat} values are nearly the same despite the void ratio gap observable in Figures 8b and 9b. Yet the 5 year-profiles in Figure 10 show a discrepancy in the k_{sat} profiles. At the very moment of a deposition, the 72% solids layers appear to be less permeable ($6x10^{-7}$ m/s at 72% solids in comparison to $8x10^{-7}$ m/s at 68% solids). This means that each freshly deposited 72% solids layer is slightly less permeable than a 68% solids deposition. The 72% solids top layer slows the dissipation of u_e with reference to the 68% solids top layer. This was not observed in the settling columns (1400 min at 72% solids versus 1440 min at 68% solids) as only self-weight effects were involved, while primary consolidation is added in the large scale progressive deposition simulations. Simulations (not presented here) confirmed that double drainage does not inhibit the influence of the top layer as hydraulic conductivities remain in the same range in the lower portion of both impoundments.

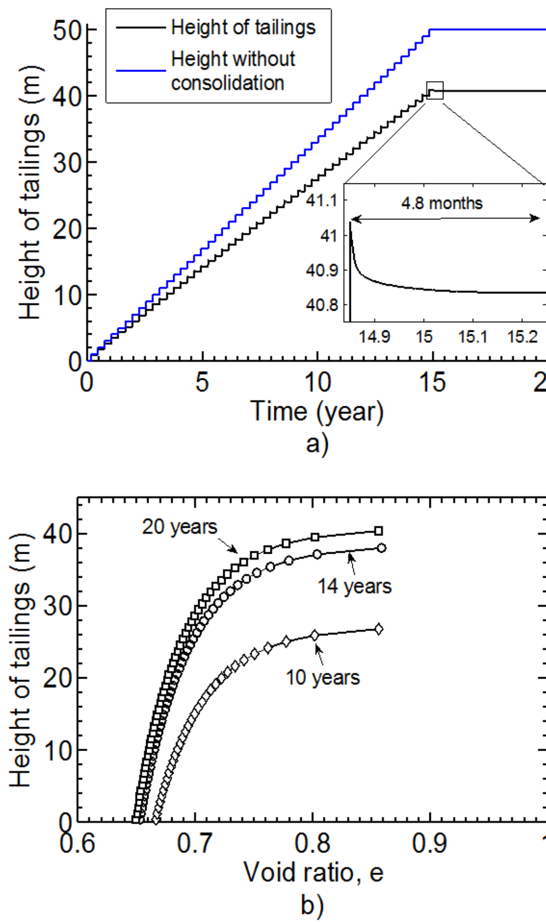

Figure 9. a) Height versus time; b) void ratio profiles at 10, 14, and 20 years (b), for a 15 year long deposition of 72% thickened tailings followed by 5 years of quiescent consolidation

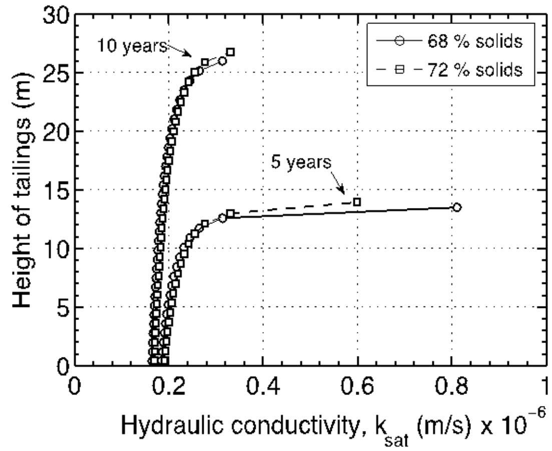

Figure 10. Comparison of hydraulic conductivity profiles at 5 years (4.95 years) and at 10 years for the 68% solids and the 72% solids impoundments

4 DISCUSSION AND CONCLUSION

This paper proposed a procedure that provides relevant information for tailings management such as the final height and void ratio profiles at various times during the deposition process. It also showed the pertinence of settling columns tests and the knowledge that can be withdrawn from such experiments when coupled to large strain models as CS2 and CS4. The suggested procedure involves fitting compressibility and hydraulic conductivity constitutive relationships of TT to self-weight consolidation experiments including pore water pressure dissipation response, settlement response and final void ratio profile. Relationships were adjusted to provide the best-fit match between the CS2 simulations and the experimental results from settling columns involving slurry thickened up to 68% solids and 72% solids. Tailings deposited at those solids content underwent self-weight consolidation only and sedimentation was negligible.

The retained constitutive relationships were then used in CS4, which shares the same numerical bases as CS2 but offers the ability to simulate accretion of soil layers. Results from CS4 suggested that self-weight consolidation and primary consolidation broadly governs the whole hydro mechanical process and that settlement occurs mainly during the operational period, i.e. during depositions.

Reliable and adequate constitutive relationships must be selected as those directly govern the consolidation behavior of the tailings impoundment. As evidenced by the CS4 results presented in this study, the final heights are very similar despite different initial void ratios and different constitutive relationships. In addition, the selected constitutive relationships lead to similar u_e dissipation delays. In the context of a 15 year-long operational period, both 68% and 72% solids impoundments show almost the same consolidation behaviour.

The initial void ratio of the slurry bears a particular importance in terms of self-weight consolidation behaviour, since the compressibility is void-ratio dependent (Imai 1981, Been and Sills 1981). Also, the initial void ratio dictates the presence and amplitude of sedimentation within the whole deposition process. The sedimentation was out of the scope of this paper, but it might still occasion important deformation over the operational period. Therefore a numerical model that accounts for sedimentation and self-weight consolidation in a unified way may be required to study the whole deformation process for tailings deposited as slurry or at low percentage of solids.

To conclude, this study demonstrated that the modeling of tailings deformations generated by primary and self-weight consolidation provides an essential understanding of the impoundment operational behaviour. This knowledge is a must with regards to the tailings deposition scheme in order to assess the storage capacity and to facilitate the raisings planning of the tailings facility.

ACKNOWLEDGEMENTS

The authors thank the geotechnical technicians of the Université de Sherbrooke for their technical support. They also thank Professor Patrick J. Fox, from the University of California, for sharing the CS4 code. Funding for this research has been provided by the National Sciences and Engineering Research Council (NSERC), the Fond Québécois pour la Recherche Nature et Technologies (FQRNT) and Golder Associés Ltée. through a BMP-Innovation Scholarship.

REFERENCES

Alexis, A., Le bras, G., and Thomas, P. 2004. Experimental bench for study of settling-consolidation soil formation, Geotechnical Testing Journal, 27(6): 557-567.

Bartholomeeusen, G., Sills, G.C., Znidarcic, D., Van Kesteren, W., Merckelbach, L.M., Pyke, R., Carrier, W.D., Lin, H., Penumadu, D., Winterwerp, H., Masala, S., and Chan, D. 2002. Sidere: Numerical prediction of large-strain consolidation, Géotechnique, 52(9): 639-648.

Been, k. and Sills, G.C. 1981. Self-weight consolidation of soft soils: An experimental and theoretical study, Géotechnique, 31(4): 519-535.

Bromwell, L.G. 1984. Consolidation of mining wastes. In Sedimentation/Consolidation Models, pp. 275-295.

Burger, R. and Concha, F. 1998. Mathematical model and numerical simulation of the settling of flocculated suspensions, International Journal of Multiphase Flow, 24(6): 1005-23.

Bussière, B. 2007. Colloquium 2004: Hydrogeotechnical properties of hard rock tailings from metal mines and emerging geoenvironmental disposal approaches, Canadian Geotechnical Journal, 44(9): 1019-1052.

Carrier III, W.D., Bromwell, L.G., and Somogyi, F. 1983. Design capacity of slurried mineral waste ponds, Journal of Geotechnical Engineering, 109(5): 699-716.

de Oliveira-Filho, W.L. and van Zyl, D. 2006. Modeling discharge of interstitial water from tailings following deposition. part 2: Application, Solos e Rochas, 29(2): 211-221.

Demers Bonin, M., Nuth, M., Dagenais, A.-.M, and Cabral, A.R. 2014. Experimental study and numerical reproduction of self-weight consolidation behavior of thickened tailings, Journal of Geotechnical and Geoenvironmental Engineering, 140(12): 1-10.

Demers Bonin, M., Nuth, M., Cabral, A.R., and Dagenais, A.-M. 2013. Self-weight consolidation behavior of thickened gold mine tailings. In GeoMontreal 2013., pp. 1-7.

Fox, P.J. and Berles, J.D. 1997. CS2: A piecewise-linear model for large strain consolidation, International Journal for Numerical and Analytical Methods in Geomechanics, 21(7): 453-475.

Fox, P.J. 2000. CS4: A large strain consolidation model for accreting soil layers. In Geotechnics of High Water Content Materials, Special Technical Publication 1374, pp. 29-47.

Gibson, R.E., England, G.L., and Hussey, M.J.L. 1967. Theory of one-dimensional consolidation of saturated clays. I. finite non-linear consolidation of thin homogeneous layers, Geotechnique, 17(3): 261-273.

Gibson, R.E., Schiffman, R.L., and Cargill, K.W. 1981. Theory of one-dimensional consolidation of saturated clays- 2. finite nonlinear consolidation of thick homogeneous layers, Canadian geotechnical journal, 18(2): 280-293.

Holdich, R.G. and Butt, G. 1996. Compression and channelling in gravity sedimenting systems, Minerals Engineering, 9(1): 115-131.

Imai, G. 1981. Experimental studies on sedimentation mechanism and sediment formation of clay materials, Soils and Foundations, 21(1): 7-20.

Jeeravipoolvarn, S., Chalaturnyk, R.J., and Scott, J.D. 2009. Sedimentation-consolidation modeling with an interaction coefficient, Computers and Geotechnics, 36(5): 751-61.

Li, H. and Williams, D.J. 1995. Sedimentation and self-weight consolidation behaviour of coal mine tailings. In Proceedings of the 1995 International Symposium on Compression and Consolidation of Clayey Soils Part 1 (of 2)., pp. 117-122.

Pane, V. and Schiffman. 1997. The permeability of clay suspensions, Geotechnique, 47(2): 273-288.

Pane, V. and Schiffman, R.L. 1985. Note on sedimentation and consolidation, Geotechnique, 35(1): 69-72.

Pedroni, L. 2011. Étude expérimentale et numérique de la sédimentation et de la consolidation des boues de traitement des eaux acides. Thèse de doctorat, École Polytechnique (Université de Montréal), Montréal, Québec, Canada.

Pu, H. and Fox, P.J. 2012. Updated CS2 model for large strain consolidation of clay. In GeoCongress 2012 Edited byAmerican Society of Civil Engineers, , pp. 115-124.

Seneviratne, N.H., Fahey, M., Newson, T.A., and Fujiyasu, Y. 1996. Numerical modelling of consolidation and evaporation of slurried mine tailings, International Journal for Numerical and Analytical Methods in Geomechanics, 20(9): 647-671.

Sills, G. 1998. Development of structure in sedimenting soils, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 356(1747): 2515-2534.

Stone, K.J.L., Randolph, M.F., Toh, S., and Sales, A.A. 1994. Evaluation of consolidation behavior of mine tailings, Journal of Geotechnical Engineering, 120(3): 473-490.

Vesilind, P.A. and Jones, G.N. 1990. A reeexamination of the batch thickening curve, Research journal of the Water Pollution Control Federation, 62: 887-893.

Yao, D.T.C. and Znidarcic, D. 1997. Crust formation and desiccation characteristics for phosphatic clays. University of Colorado at Boulder, Boulder, Colorado, United States.