Assessing Oil Sands Tailings Consolidation Parameters Relative to Long-term Reclamation

H. Rourke and D. Hockley
SRK Consulting, Vancouver, BC, Canada

ABSTRACT: The reclamation of tailings deposits is dependent upon long-term consolidation, which determines both the final storage volume and ultimate deposit strength. Very soft materials like flocculated mature fine tailings undergo large deformations during consolidation. Describing this "large strain consolidation" requires non-linear equations for compressibility and hydraulic conductivity as functions of void ratio or effective stress. Typically, these equations are input to a finite strain consolidation model to estimate overall consolidation rates. This paper presents a robust sensitivity analysis to examine the effects of material property functions and design variables on consolidation model results. The tested variables included compressibility constants, hydraulic conductivity constants, years of deposition, rate of rise, specific gravity, initial solids content, and surcharge load application. Interpretation of the results identified clear patterns and dimensionless groupings that can be used as indicators of ultimate consolidation performance.

1 INTRODUCTION

The large inventory of mature fine tailings and the need to reclaim tailings deposits is a major challenge for the oil sands industry. Reclamation plans commonly include capping and revegetating tailings surfaces, which requires the tailings to develop sufficient strength to support construction equipment. Oil sands operators currently apply a variety of methods to treat fluid tailings. Initial water removal is achieved through flocculant addition followed by thickening, centrifugation or air drying. Further dewatering and strength gain is governed by the material's consolidation behavior. Factors affecting consolidation include the hydraulic conductivity and compressibility properties of the tailings, as well as design variables such as deposition rates (rate of rise) and ultimate depth. But the interactions among these variables are non-linear, making it difficult to know exactly which variable should be changed in order to achieve "better" consolidation. The objective of this study is to understand how the interaction of material properties and design variables affect the consolidation of flocculated mature fine tailings. The hope is that such an understanding will help focus research efforts and operational strategies for creating reclaimable deposits within reasonable timeframes.

2 METHOD

2.1 Overview of consolidation theory

The classic one-dimensional Terzaghi consolidation theory was published in 1925 and is represented by Equation 1:

$$\frac{c_v \partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \tag{1}$$

Where:

c_v = coefficient of consolidation
u = pore pressure
z = depth
t = time

The Terzaghi relationship assumes that compressibility and hydraulic conductivity are constant and not affected by changes in void ratio. This is appropriate for small-strain applications common in foundation design, but not for soft tailings deposits that can undergo large deformations and very significant changes in void ratio. For these applications, finite strain theory is needed. The Gibson finite strain theory (Gibson 1967 and 1981) is shown in Equation 2.

$$\pm\left(\frac{\rho_s}{\rho_f} - 1\right)\frac{d}{de}\left[\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z} + \frac{\partial}{\partial z}\left[\frac{k(e)}{\rho_f(1+e)}\frac{d\sigma\prime}{de}\frac{\partial e}{\partial z}\right] + \frac{\partial e}{\partial t} = 0 \tag{2}$$

Where:

ρ_s = solids density
ρ_f = fluid density
k = hydraulic conductivity
e = void ratio
σ' = effective stress
z = depth
t = time

Two constitutive relationships, describing the changes in compressibility and hydraulic conductivity as the material consolidates, are needed to solve the equation (2). There is continued debate and research about the most appropriate compressibility-void ratio relationship (e-logσ’). Proposed representative relationships vary from power law, to modified power law, to Weibull functions. For the purposes of this paper, a widely-used power law function is applied:

$$e = A\sigma^B \tag{3}$$

Where:

e = void ratio
σ = effective stress
A = unique material constant
B = unique material constant

The hydraulic conductivity-void ratio relationship (k-e) is also commonly modelled using a power function:

$$k = Ce^D \tag{4}$$

Where:

k = hydraulic conductivity
C = unique material constant
D = unique material constant

Before looking at how these functions interact, a good starting point is to look at the constitutive relationships on their own. The effect of the A and B values on the shape of the compressibility function is shown in Figure 1. The effect of the C and D values on the shape of the hydraulic conductivity function is shown in Figure 2.

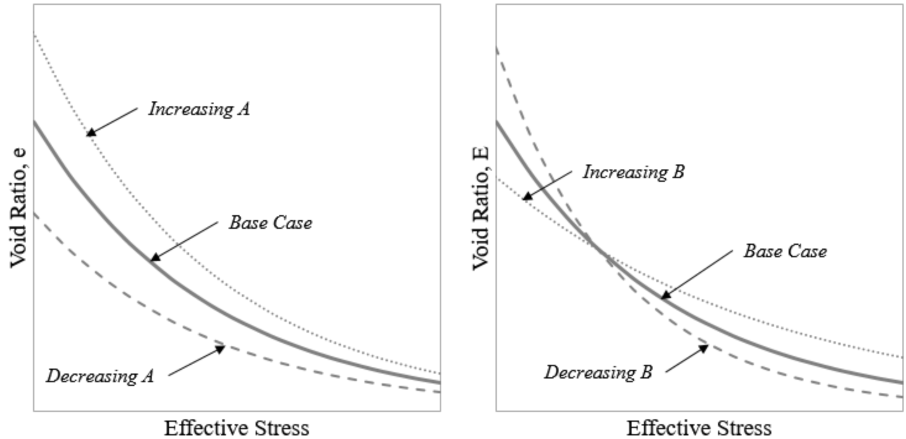

Figure 1. Effect of A and B values on compressibility

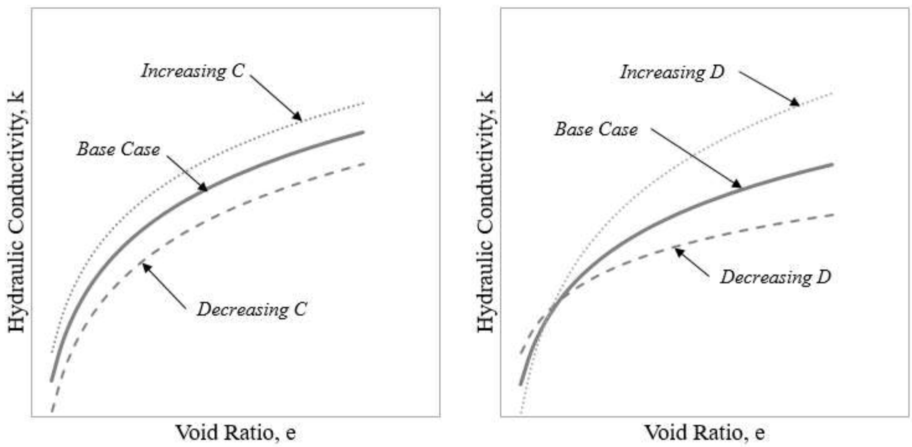

Figure 2. Effect of C and D values on hydraulic conductivity

2.2 *Modeling Approach*

To understand the combined effects of the hydraulic conductivity and compressibility functions, it is necessary to run a full consolidation model that also considers stresses associated with tailings deposition, porewater pressure, and physical characteristics such as specific gravity and initial solids content. This study used the one-dimensional finite strain program FSConsol© (Version 3.49; GWP Software 1996).

The model was run in a sensitivity analysis mode, allowing the influence of each input parameter on final outcomes, such as the time to 90% consolidation, to be tested. A Python script was written and used to automate the modelling process. This allowed the authors to run the hundreds of models required to perform a complete parametric analysis. Over 700 models were run in total, and each model was run for a 1000 year simulation period.

The key input parameters and ranges tested in the sensitivity runs are summarized in Table 1. Compressibility and hydraulic conductivity data sources include both laboratory and field measurements of flocculated mature fine tailings. While laboratory compressibility estimates are generally representative of field behavior, laboratory hydraulic conductivity results commonly underestimate field scale values by 3-10 times (COSIA 2014, Masala et al. 2014, Hockley 2017). To account for this, laboratory hydraulic conductivity estimates were increased by a factor of 5 to develop the ranges shown in Table 1.

Table 1. Typical ranges of consolidation inputs found in literature

Parameter	**Base Case**	**Min**	**Max**	**Reference**
Rate of rise (m/year)	5	1.5	10	Experience
Years of deposition	20	10	50	Experience
Applied surcharge (kPa)(1)	36	0	90	Experience
Compressibility (kPa) constants				Masala *et al.* 2010,
• A	3.2	2.8	3.5	Jeeravipoolvarn 2010,
• B	-0.25	-0.30	-0.18	Znidarcic 2016
Hydraulic conductivity (m/s) constants(2)				Masala *et al.* 2010,
• C	2.5E-10	5.0E-11	5.0E-10	Jeeravipoolvarn 2010,
• D	4.0	3.3	6.0	Znidarcic 2016
Specific gravity (SG)	2.50	2.45	2.65	Masala *et al.* 2010, Jeeravipoolvarn 2010, Znidarcic 2016
Solids content (SC)	35%	20%	50%	COSIA 2014

(1) Base case surcharge of 36 kPa represents an approximate 2 m soil cap; maximum surcharge represents a 5 m soil cap

(2) Laboratory hydraulic conductivity have been increased by a factor of 5 to account for the difference between laboratory and field-scale measurements

Sensitivity analyses were first run by varying each input parameter individually. Next the following multiple parameters scenarios were run to understand the combined effects:

- A and B to assess combined compressibility effects
- C and D to assess combined hydraulic conductivity effects
- A, B, C, D to assess combined consolidation effects
- Years of deposition and rate of rise to assess combined operational effects

Three results of each model run were recorded and used in the further analysis:

- Time to reach 90% consolidation, as an indicator of reclamation timeframes;
- Height after 1000 years, as an indicator of volume reduction; and
- Solids content after 1000 years, as an indicator of shear strength.

3 RESULTS

3.1 Overall Ranges

Results of all the sensitivity runs are summarized in Table 2. The first two columns indicate the tested parameter and range of values, and the next six columns show the range of model results. For each result, the corresponding parameter value is shown underneath in parentheses.

Table 2. Summarized Results Over 1000 Year Simulation Period

Parameter	Tested Values	Time to 90% Consolidation (years)		Minimum Height (m) after 1000 years		Maximum Solids Content (% Solids) after 1000 years	
Base Case	See Table 1	197		33.8		73.3%	
		Best	**Worst**	**Best**	**Worst**	**Best**	**Worst**
Individual-variable runs							
Rate of rise (m/year)	1.5 to 10	85 *(1.5)*	409 *(10)*	10.6 *(1.5)*	70.3 *(10)*	73.3% *(1.5)*	71.4% *(10)*
Years of deposition	10 to 50	126 *(10)*	488 *(50)*	17.3 *(10)*	90.5 *(50)*	73.3% *(20)*	70.6% *(50)*
Surcharge (kPa)	0 to 90	243 *(90)*	302 (0)	32.2 *(90)*	36.9 *(0)*	75.3% *(90)*	69.8% *(0)*
A (kPa)	2.8 to 3.5	254 *(3.5)*	309 *(2.8)*	32.4 *(2.8)*	35.0 *(3.5)*	75.0% *(2.8)*	71.9% *(3.5)*
B	*-0.18 to -0.32*	*152* *(-0.18)*	352 *(-0.32)*	31.2 *(-0.32)*	40.1 *(-0.18)*	76.6% *(-0.32)*	66.5% *(-0.18)*
C (m/s)	5E-10 to 5E-11	192 *(5E-10)*	564 *(5E-11)*	33.3 *(5E-10)*	41.5 *(5E-11)*	73.9% *(5E-10)*	65.1% *(5E-11)*
D	3.25 to 6	278 *(4)*	360 *(3.25)*	33.6 *(6)*	34.2 *(3.25)*	73.6% *(6)*	72.9% *(3.25)*
Specific Gravity	2.45 to 2.65	258 *(2.65)*	287 *(2.45)*	32.0 *(2.65)*	34.5 *(2.45)*	74.8% *(2.65)*	72.8% *(2.45)*
Initial % Solids	20% to 50%	159 *(20%)*	558 *(50%)*	17.8 *(20%)*	55.5 *(50%)*	73.3% *(35%)*	72.4% *(20%)*
Multiple-variable runs							
A and B		132 *(A=3.5 B-0.18)*	357 *(A=2.8 B=-0.3)*	31.4 *(A=3 B=-0.3)*	42.1 *(A=3.5 B=-0.18)*	77.2 *(A=2.8 B=-0.3)*	64.5 *(A=3.5 B=-0.18)*
C and D		182 *(C=5E-10 D=3.5*	699 *(C=5E-11 D=3.5)*	33.3 *(C=5E-10 D=5)*	45.6 *(C=5E-11 D=3.5)*	73.9 *(C=5E-10 D=5)*	61.3 *(C=5E-11 D=3.5)*
A, B, C, D		35 *(A=3.5 B=-0.18 C=5E-10 D=6)*	708 *(A=2.8 B=-0.3 C=5E-11 D=3.5)*	29.1 *(A=2.8 B=-0.3 C=5E-10 D=3.5)*	47.2 *(A=3.5 B=-0.18 C=5E-11 D=3.5)*	79.6 *(A=2.8 B=-0.3 C=5E-10 D=3.5)*	60.0 *(A=3.5 B=-0.18 C=5E-11 D=3.5)*
Rate of Rise and Years of Deposition		45 *(2 m/yr 10 years)*	578 *(10 m/yr 50 years)*	5.4 *(1.5 m/yr 10 years)*	205.5 *(10 m/yr 50 years)*	73.3 *(10 m/yr 10 years)*	65.4 *(10 m/yr 50 years)*

3.2 Time for 90% consolidation

It is possible to plot results of the 700 sensitivity runs in many ways. As a simple example, Figure 3 illustrates the effects of the model inputs on the range of time to reach 90% consolidation. The first two rows are unsurprising. Varying all of the consolidation parameters A, B, C and D creates a very wide range in results. Rate of rise and years of depositions together determine the overall depth of the deposit, and therefore also have a strong effect on consolidation times.

The remaining rows are more informative. They show that the hydraulic conductivity parameters C and D are very influential, and that C is more influential than D, at least over the ranges tested here. The compressibility parameters A and B are less influential, in part because the 90% consolidation endpoint partially accounts for the compressibility curve. Initial solids content has a predictably strong effect, but the surcharge loading has very little effect.

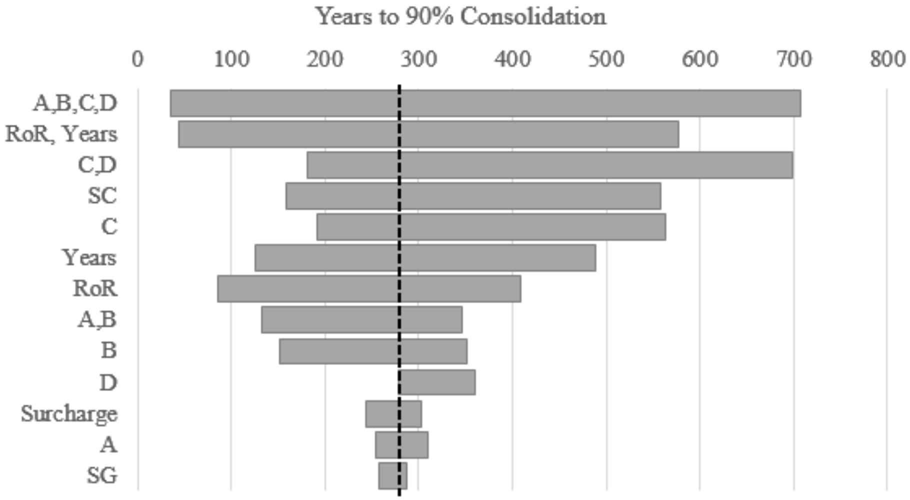

Figure 3. Years to 90% consolidation

3.3 Combined effect of hydraulic conductivity and compressibility parameters

Figures 4 and 5 show another way to plot the sensitivity results. Figure 4 shows the combined influence of the compressibility parameters A and B on reclamation times. The "bubbles" on the plot show the number of years required to reach an average solids content of 65%, with larger bubbles representing longer times.

The smallest bubble, indicating the fastest consolidation time, is at the top right-hand corner of the graph when A and B are at their highest values of 3.5 and -0.18, respectively. The trends clearly show that increasing either A or B, or both, improves consolidation times.

Looking at the first column, for a constant B value of -0.3, the consolidation time varies from 357 years when A is 2.8 to 324 years when A is 3.5. Looking at the bottom row, for a constant A value of 2.8, the consolidation times vary from 357 years when B is -0.3 to 188 years when B is -0.18. Clearly changes to B have a much greater effect on consolidation times than changes to A, over the ranges tested here.

Figure 5 uses a similar format to show the effects of the hydraulic conductivity constants C and D on the time to reach an average solids content of 65%. By following the same line of reasoning as presented above, it is clear that C is more influential than D. Interestingly, the effect of D depends on C. For example, when C is high (in the top row) increasing D leads to increasing consolidation times, but when C is low (bottom row) increasing D leads to reduced consolidation times. The underlying reasons for this are apparent from a close inspection of Figure 2.

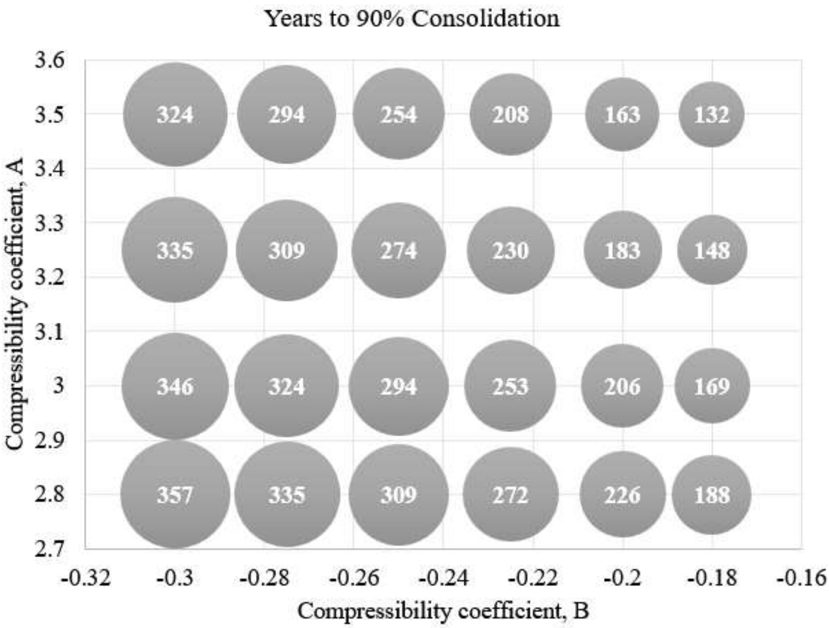

Figure 4. Effects of compressibility parameters on time to reach 90% consolidation

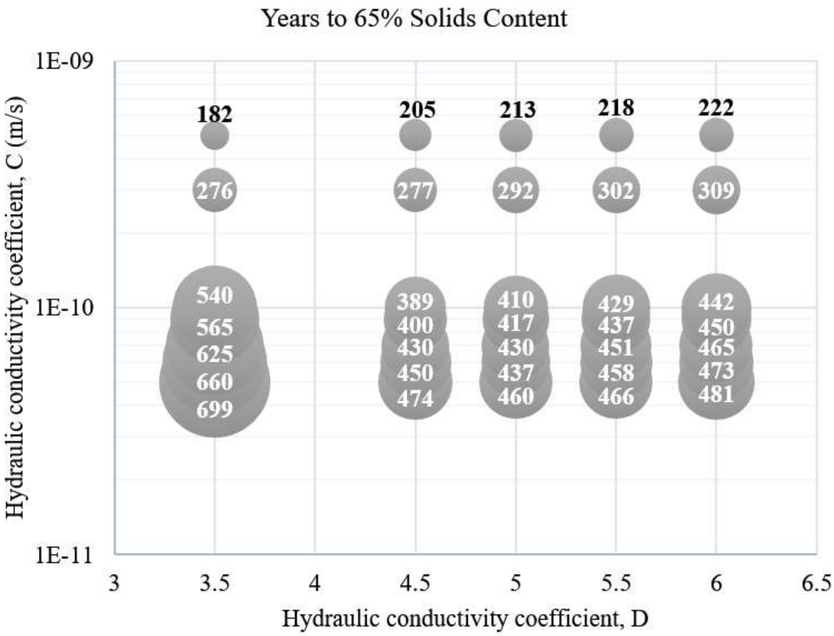

Figure 5. Effects of hydraulic conductivity parameters of time to reach 65% solids

4 DISCUSSION

4.1 Dimensionless Rate of Rise

Deriving further insights from the sensitivity analyses requires that the 700 sets of results be collapsed to simpler forms. One method to look for underlying patterns in complex information is dimensional analysis (Cimbala and Cengel, 2006). Briefly, the method consists of defining dimensionless combinations of parameters, and then converting results to those dimensionless forms in the hopes that "universal" patterns become more evident.

Figure 6 shows an example. It converts the rate of rise and hydraulic conductivity to a "dimensionless rate of rise" on the x-axis. (The plot shows the case where hydraulic conductivity is calculated at a void ratio of 3.0, but a similar plot is obtained with other void ratios.) The y-axis is another dimensionless quantity obtained by dividing the deposit height reached at the end of tailings deposition to the product of rate of rise times years of deposition. The product is in fact the height that would be reached if there were no consolidation during deposition. The resulting dimensionless quantity varies between 0.4 and 1 over the ranges of inputs tested, with higher values indicating that there has been less removal of pore water during the deposition period. Inspection of the curve shows that, when the dimensionless rate of rise on the x-axis exceeds about 10, there is little or no consolidation during deposition. In other words, when actual rates of rise are more than 10 times the hydraulic conductivity, all of the excess water is trapped in the initial deposit. Consolidation times and settlement depths would be correspondingly high.

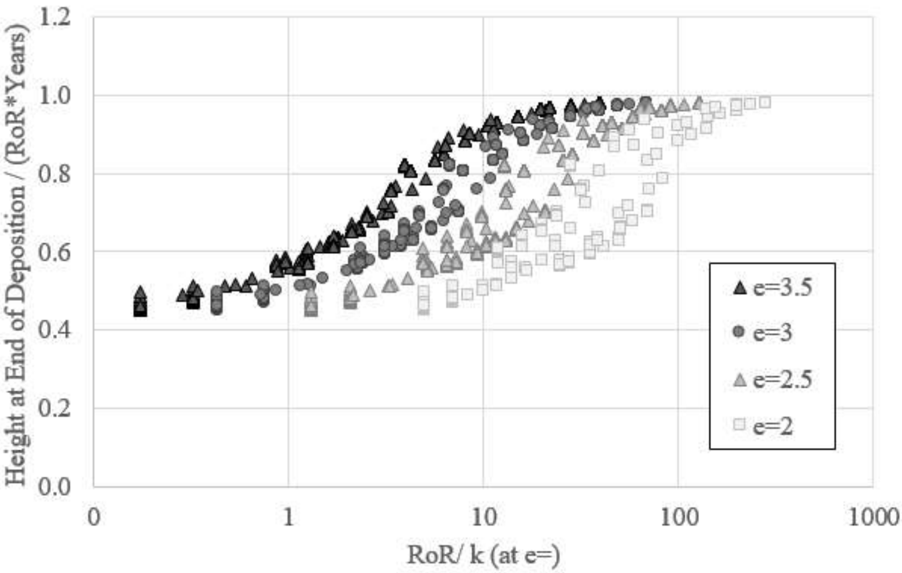

Figure 6. Dimensionless rate of rise vs dimensionless deposit height

4.2 Coefficient of consolidation

In Terzaghi theory, the coefficient of consolidation, c_v, is used to represent the combined effect of hydraulic conductivity and compressibility and allow dimensionless solutions of the consolidation equation. The coefficient of consolidation c_v is calculated as:

$$c_v = \frac{k(1+e)}{a_v \gamma_w} \tag{7}$$

Where:

k	=	hydraulic conductivity
e	=	void ratio
a_v	=	coefficient of compressibility
γ_w	=	unit weight of water

The same concept can be used in large-strain theory but c_v becomes a function of effective stress (or void ratio) rather than a constant. Figure 7 illustrates the value of c_v as a predictor of consolidation time. The x-axis in this case has also been "dimensioned" by dividing c_v by the square of the initial deposit height. That seems arbitrary but in reality, it simply adjusts for the effect of the different initial conditions. (The c_v value in Figure 7 were all calculated at e=2.5, which is entirely arbitrary, but a similar figure is obtained with other choices.)

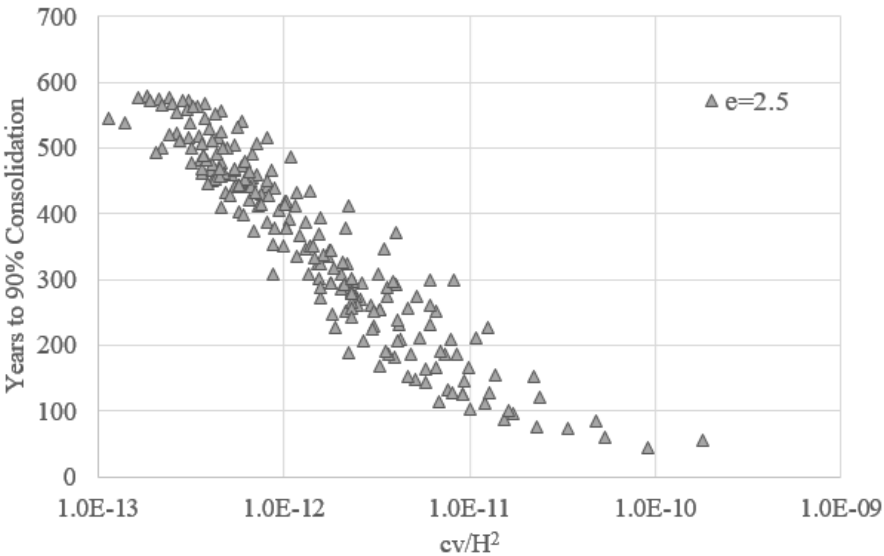

Figure 7. Consolidation time versus c_v/H^2 [1]

All of the c_v functions resulting from the sensitivity runs are plotted against effective stress in Figure 8. The results show a wide range of c_v values. More surprising perhaps is the diversity in how the c_v values change with increasing effective stress: some plots increase by orders of magnitude, some decrease by orders of magnitude, and some stay constant. Determining the significance for consolidation times takes some further thought. Clearly the best case is a constant high c_v such as shown on the bottom right plot in Figure 8. Cases where the c_v function slopes upward indicate that c_v values will increase as consolidation proceeds, (i.e. consolidation will accelerate)

[1] Note: D values were kept constant to reduce scatter in Figure 7.

and are likely to lead to overall faster consolidation than cases where the c_v function slopes downward.

In terms of the input parameters, there a clear relationship between B and D values and the slope of the c_v functions in Figure 8. Increasing (less negative) B values result in upward sloping c_v functions. Increasing D values lead to initially high c_v functions, but with strongly negative slopes. The differences within the family of curves shown in each plot represent the effects of the A and C coefficients. Changing the C coefficient shifts the c_v function upward by up to an order of magnitude, whereas changing A less than half an order of magnitude effect.

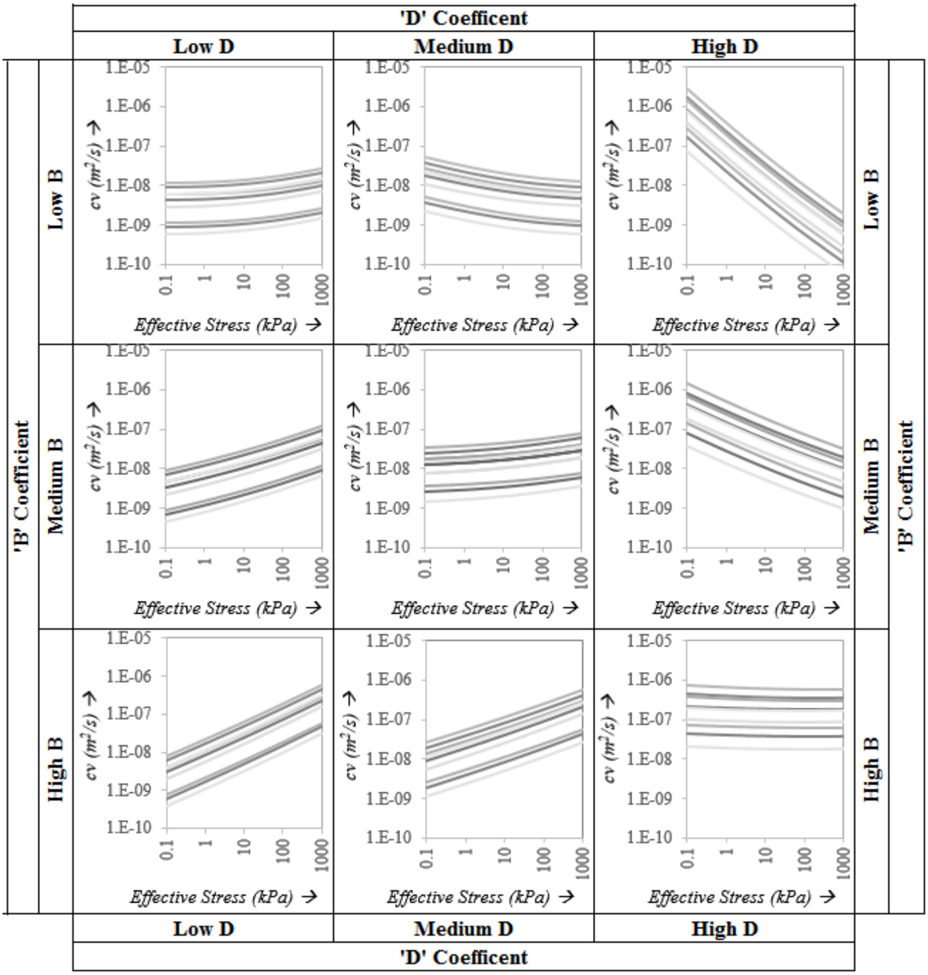

Figure 8. Coefficient of consolidation (c_v) functions from 700 sensitivity runs

4.3 Practical implications

There are three key performance issues associated with the successful reclamation of oil sands tailings deposits:

1. transforming mature fine tailings deposit into sustainable dry closure landscapes requires the tailings to have sufficient strengths to support construction equipment and allow cover construction ;
2. there is currently a large inventory of mature fine tailings stored in above-ground tailings facilities that require volume reduction; and
3. reclamation times are currently very slow with deep deposits requiring hundreds to thousands of years to reach desired closure strengths and/or volumes.

If the primary goal is to develop high shear strengths, a key performance indicator is the solids content achieved at a point in time. Table 2 shows that material properties are more influential than operational practices in increasing the 1000-year solids content of the deposit. For this case, increasing compressibility is more important than increasing hydraulic conductivity.

If the primary goal is to reduce overall deposit volumes, a key performance indicator is the height of the deposit at a point in time. Table 2 shows that operational practices are most important and that 1000-year heights can be greatly reduced by depositing less material at a slower rate. Initial solids content also has a significant effect, as does increasing compressibility.

Increasing shear strengths and reducing volumes has little benefit if it requires hundreds or thousands of years to do so. Therefore, the primary goal is often reducing reclamation timeframes. Both improving material properties (such as consolidation parameters) and operational practices (such as the rate of rise) are important. The most influential parameters are the initial solids content, hydraulic conductivity constant, C, the number of years of deposition, and rate of rise. For this case, increasing the hydraulic conductivity is most important and the compressibility has a lesser effect.

An important use that the authors see for these patterns is to direct development of new mature fine tailings treatments toward material properties that have the greatest influence on desired outcomes. A very practical example would be the pattern showing the importance of the hydraulic conductivity constants. Given that lab scale methods have difficulty measuring representative hydraulic conductivities, this finding might indicate a much greater need for field scale testing.

5 SUMMARY AND CONCLUSIONS

This study undertook a parametric sensitivity analysis to examine the effect of material properties and design variables on tailings consolidation. The material properties tested covered the range of flocculated mature fine tailings in the oil sands literature. Findings to date include the importance of the hydraulic conductivity function for determining consolidation times, relationships between rate of rise and the extent of initial consolidation, and the complex influence of both compressibility and hydraulic conductivity inputs on coefficients of consolidation.

Limitations of this study and possible avenues for further work include the following:

- Only one compressibility function was tested in the analyses. Further work could test the influence of alternative functions, such as the Weibull or modified power law relationships.
- Compressibility and hydraulic conductivity inputs only included ranges found in publicly available literature for flocculated mature fine tailings.
- Only four multiple-variable scenarios were tested as described earlier. Given that there were 5 to 7 values tested for each of the nine input variables, thousands of runs would be required to test every combination of multiple-variable scenarios. The results of this work could be used to identify key combinations of variables that warrant testing in future analyses.

6 REFERENCES

Alberta Energy Regulator (AER) Directive 085 October 12 2017 Fluid Tailings Management for Oil Sands Mining Projects. https://www.aer.ca/documents/directives/Directive085.pdf

Cimbala, J.M. and Cengel, Y.A.. (2006) *Fluid Mechanics: Fundamentals and Applications*, Boston, McGraw-HillHigher Education

COSIA (2014) Guidelines for Performance Management of Oil Sands Fluid Fine Tailings Deposits to Meet Closure Commitments. *Canadian Oil Sands Innovation Alliance*, February, 2014, 19 pp.

Gibson, R.E., English, G.L., and Hussey, M.J., (1967) The Theory of One Dimensional Consolidation of Saturated Clays. *Geotechnique*, 17, 2, pp.261-273

Gibson, R.E., Shiffman, R.L., and Cargill, K.W., (1981) The Theory of One-Dimensional Consolidation of Saturated Clays II. *Can Geotech Journal*, 18, 2, pp.280-293

GWP Software Inc (1996). FSConsol Computer Software, Version 3.49. Retrieved from: http://www.fscon-sol.com/

Hockley, D., (2017) Clay effects on tailings geotechnical properties. *In: Clay in Oil Sands (O. Omotoso and D. Hockley, editors). Workshop Lecture Series,* 22, The Clay Minerals Society, Chantilly, Virginia, USA.

Jeeravipoolvarn, S. (2010) *Geotechnical behaviour of in-line thickened oil sands tailings*. PhD thesis, Geotechnical Engineering, University of Alberta, Edmonton, AB, 431 pp.

Locat, J., and Demers, D. (1988) Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays. *Canadian Geotechnical Journal*, 24, 4, pp. 799-806.

Masala, S., Nik, R.M., Freeman, G., and Mahood, R. (2014) Geotechnical insights into deposition, dewatering and strength performance of thickened and paste tailings deposits at Shell Canada's tailings test facility. Pp. 277-288 in*: Fourth International Oil Sands Tailings Conference (IOSTC), 7-10 December 2014, Lake Louise AB (D.C. Sego, W. Wilson and N.A. Beier, editors).* University of Alberta, Edmonton, AB.

McKenna, G., Mooder, B., Burton, B., and Jamieson, A. (2016) Shear strength and density of oil sands fine tailings for reclamation to a boreal forest landscape. Pp. 130–153 in: *Fifth International Oil Sands Tailings Conference (IOSTC) (D.C. Sego, W. Wilson, and N.A. Beier, editors).* University of Alberta, Edmonton, Alberta, Canada.

Miller, W.G, Scott, J.D., and Sego, D.C. (2010a) Effect of extraction water chemistry on the consolidation of oil sands fine tailings. *CIM Journal*, 1, 2, pp. 113-129.

Miller, W.G, Scott, J.D., and Sego, D.C. (2010b) Effect of the extraction process on the characteristics of oil sands fine tailings. *CIM Journal,* 1, 2, pp. 93-112.

Wood, D.M. (1990*) Soil Behaviour and Critical State Soil Mechanics*, Cambridge University Press, Cambridge

Znidarcic, D., Van Zyl, D., Ramirez, M., Mittal, K., and Kaminsky, H. (2016) Consolidation characteristics of flocculated MFT – Experimental column and SICT data. Pp. 408-415 in*: Fifth International Oil Sands Tailings Conference (IOSTC), Lake Louise Alberta, Canada (D.C. Sego, W. Wilson, and N.A. Beier, editors).* University of Alberta, Edmonton, Alberta, Canada.