Benchmarking of Large-Strain Consolidation, Sedimentation, and Creep Process for Oil-Sands Tailings

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ABSTRACT

Recent efforts in numerical modeling of the tailings consolidation processes for oil-sands tailings have raised fundamental questions related to the processes of large-strain consolidation and sedimentation. At which point does consolidation dominate? What about the sedimentation process? What about creep? The numerical modeling of the consolidation of oil-sand tailings becomes challenging if the fundamental process has not yet been established. This paper examines each of these three theories and how they relate to existing benchmarks. The performance of individual processes of large-strain consolidation, sedimentation, and the creep processes are studied. The benchmarking of single and multi-stage consolidation models is examined in light of their application the layered deposition currently proposed in industry. The performance of each theory in light of Standpipes 1 & 3 from the University of Alberta is examined in light of how each theory matches reality. The performance of each theory related to oil-sand and non-oil-sand materials is examined and reviewed. From this paper it is desired that further clarity relating to the reasonable application of each theory can be obtained for future studies and applications of the numerical methodology.

KEY WORDS

Numerical modeling, oil-sands tailings, large-strain consolidation, sedimentation, creep

1 INTRODUCTION

Oil-sands mining operations in Northern Alberta produce enormous volumes of high water content tailings composed of sand, silt, clay, and a small amount of bitumen. The disposal or deposition of the tailings poses a challenge to the engineers because of its unique long-term settlement behavior. The very slow consolidation behavior of this material is believed to be caused by the extensive clay dispersion from the Clark hot water extraction process that dictates chemical interaction between clay, water, and residual bitumen and results in a significant reduction of the material's hydraulic conductivity (Jeeravipoolvarn et al. 2009). The University of Alberta established two 10 m high, 0.9 m diameter standpipes in 1982 filled with oil-sands fine tailings in one standpipe and a mix of the fine tailings and tailings sand in the second standpipe to investigate and understand the long-term consolidation behavior of the fine tailings. The second standpipe was subsequently emptied and refilled with a new mix of material after 2 years and termed as standpipe 3 (Jeeravipoolvarn et al. 2009). In the oil-sands industry, fines are defined as <45 µm.

Several researchers (Jeeravipoolvarn et al. 2008a, 2009; Pollock 1988; Suthaker 1995) have attempted to numerically predict or match the experimental data using large-strain consolidation (LSC) theory (Gibson et al. 1967, 1981; Somogyi 1980). However, the application of large-strain consolidation theory to predict the compression behavior of oil-sands fine tailings did not provide a satisfactory agreement with the experimental data (Jeeravipoolvarn et al. 2008a). This issue of disagreement leads to the question: "What is missing in the consolidation theory?" This indicates that there is either a lack of proper constitutive relationships for the problem or the correct physics of the problem is yet to be understood.

In order to look for other possible mechanism affecting the compression behavior of the oil-sands tailings, some researchers (e.g. Masala 1998) have considered a coupled sedimentation and consolidation approach for the numerical simulations to standpipe materials with limited success. Masala (1998) used the concept of permeability as the unifying principle of sedimentation and consolidation. Masala (1998) noted that coupled models were mathematically difficult to solve because the sedimentation equations were introducing discontinuities into the solution when using Eulerian coordinate frame.

Other researchers (Jeeravipoolvarn et al. 2009; Scott et al. 2004) have argued that the tailings was, in fact, creeping and not consolidating since a very trivial amount of effective stress was developed with a significant amount of settlement (approximately 3.5 m by self-weight over 30 years). In other words, there appears to have a reduction in void ratio without considerable effective stress development for standpipe 1 material. It was, therefore, suggested that the time rate of compression be included in compressibility relationship (Bartholomeeusen 2003; Bjerrum 1967; Leroueil et al. 1985) in order to consider the creep in consolidation. However, the numerical predictions incorporating creep in the consolidation model by Jeeravipoolvarn et al. (2008a) found no improvement in the settlement predictions.

Given the large discrepancy between the numerical predictions on oil-sands fine tailings and experimental observation, and complex phenomena, this article presents three different approaches; large-strain consolidation, sedimentation, and the creep process of analyzing the long-term settlement behavior of oil-sands tailings.

2 STANDPIPE TESTS

The 10 m standpipes were established at the University of Alberta laboratory in 1982 and monitored for 30 years in a fairly consistent temperature of around 21 °C before decommissioning in 2012. Standpipe 1 was filled with oil-sands fine tailings. The tailings were brought from Syncrude's Mildred Lake tailings pond. Standpipes 2 and 3 are filled with mixes of fine tailings and sand of 48% sand and 82% sand, respectively. They were designed for studying the effects of entrained sand on the consolidation behavior (Jeeravipoolvarn et al. 2009). This study considers the numerical studies of standpipes 1 and 3 materials only because the standpipe 2 was discontinued after approximately 2 years of operation and refilled with a new mix of material. This new mix was termed standpipe 3. The properties of material placed in standpipes 1 and 3 are shown in Table 1.

Table 1. Tailing properties (After Jeeravipoolvarn et al. 2009).

Property	Standpipe 1	Standpipe 3
Initial solids content (%)	30.6	74.8
Initial water content (%)	226.8	33.7
Sand content (% by dry mass)	11.0	82.0
Fines content (% by dry mass)	89.0	18.0
Bitumen content (% by total mass)	3.1	1.2
Initial bulk density (kg/m^3)	1210	1850
Initial void ratio, e_0	5.17	0.87
Initial fines void ratio	5.00	4.15
Initial fines water ratio (FWR)	28.2	2.58
Specific gravity, G_s	2.28	2.58
Sand fines ratio (SFR)	0.12	4.56

Note: Fines content is mass of fines and bitumen divided by total mass of solids; fines void ratio is volume to void divided by volume of fines and bitumen; fines water ratio (FWR) is mass of fines and bitumen divided by mass of fines, bitumen, and water; and sand fines ratio (SFR) is defined as mass of sand divided by mass of fines and bitumen.

3 CONVENTIONAL LARGE-STRAIN CONSOLIDATION MODELING

Oil-sand tailings are compressible and strains are comparatively large. Traditional soil consolidation theories with infinitesimal strain requirements are inadequate. One-dimensional non-linear large-strain consolidation equation formulated by Gibson et al. (1967, 1981) has been used as the basis for long-term consolidation analysis of soft clay layers like oil-sands tailings. The governing equation is expressed in terms of void ratio, given in Equation 1:

$$\pm\left(\frac{\rho_s}{\rho_f}-1\right)\frac{d}{de}\left[\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z}+\frac{\partial}{\partial z}\left[\frac{k(e)}{\rho_f(1+e)}\frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right]+\frac{\partial e}{\partial t}=0 \tag{1}$$

where e is void ratio, ρ_f and ρ_s are densities of fluid and soil phases, σ' is effective stress, z is material coordinate, t is time, $k(e)$ defines as hydraulic conductivity is the function of void ratio.

The above equation is reformulated by Somogyi (1980) to facilitate mathematical solution and expressed in terms of excess pore pressure instead of void ratio. The reformulated equation has been used for modelling the oil-sand tailings behavior by many researchers (Jeeravipoolvarn 2005; Jeeravipoolvarn et al. 2008a, 2009; Suthaker 1995). The reformulated equation is expressed as (Jeeravipoolvarn et al. 2008b):

$$\frac{\partial}{\partial z}\left[\frac{k(e)}{\gamma_w(1+e)}\right]\frac{\partial u}{\partial z}+\frac{k(e)}{\gamma_w(1+e)}\frac{\partial^2 u}{\partial z^2}+\frac{de}{d\sigma'}\frac{\partial u}{\partial t}-\frac{de}{d\sigma'}\left[(G_s-1)\gamma_w\frac{d(\Delta z)}{dt}\right]=0 \tag{2}$$

where k is hydraulic conductivity, γ_w is unit weight of water, u is excess pore-water pressure, and G_s is specific gravity.

The large-strain consolidation analysis is performed by using two important constitutive relationships: (i) compressibility relationship relating the effective stress and void ratio, and (ii) hydraulic conductivity relationship relating the hydraulic conductivity and void ratio. These relationships are directly determined from a large-strain consolidation test. A power law function or a Weibull function (Jeeravipoolvarn et al. 2008a) provides a reasonable fit relating the void ratio in terms of effective stress data and is frequently adopted in the numerical simulations. These functions are expressed as:

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

$$e=A-B\exp\left(-E\sigma'^{F}\right) \tag{4}$$

where A, B, E, and F are curve-fitting parameters.

The measurement of hydraulic conductivity is relatively more challenging (Suthaker & Scott 1996) than measuring the compressibility data and the measured hydraulic conductivity data for standpipe 1 shows considerable spread (Figure 2). Such a spread of data could be partly due to non-Darcian behavior of the mature fine tailings (MFT) material as the hydraulic conductivity is dependent on the hydraulic gradient and bitumen content (Suthaker & Scott 1996, 1997). Hydraulic conductivity value can also be affected by a channeling effect (Jeeravipoolvarn et al. 2008a). The hydraulic conductivity of the fine tailings is often expressed in a power law form in terms of void ratio in numerical simulations.

$$k=Ce^{D} \tag{5}$$

where C and D are curve-fitting parameters.

4 COUPLED SEDIMENTATION AND CONSOLIDATION PROCESS

Because of low initial solids content of oil-sands tailings, the disposal of tailings slurry has forced a realization that there could be a point at which the void ratios are high and material behavior is governed by sedimentation rather than consolidation theory. For oil-sands fine tailings with low solids concentration and high water content, particles may settle together (unlike the fall of particles individually in free sedimentation) as if they were in a spatial network. This is known as hindered settling in Kynch's (1952) terminology and its existence in soil has been studied by McRoberts & Nixon (McRoberts & Nixon 1976). During the sedimentation process the soil that is formed beneath the hindered settling zone may undergo consolidation. Thus, a mathematical treatment of concomitant occurrence of sedimentation and consolidation may have possible application.

Although the theories of sedimentation (Kynch 1952) and consolidation (Terzaghi 1943) were developed independently in different areas in the past, subsequent researches (Been & Sills 1981; Been 1980; Toorman 1996, 1999) were able to link the two to develop a unified theory of sedimentation and consolidation. Masala (1998) studied the coupled sedimentation and consolidation process on standpipes with limited success.

The present study utilizes the coupled sedimentation and large-strain consolidation theory proposed by Fredlund et al. (2012). The concept of "hindered settling velocity" is required when modeling the sedimentation and consolidation processes associated with the use of the extended Somogyi formulation. The sedimentation process is governed by the settling velocity when effective stress becomes less than a critical value. If a constant settling velocity is assumed, the sedimentation process can be described by the Kynch (1952) equation and solved using the analytical analysis presented by McRobert & Nixon (1976). The concentration of particles has a significant influence on the settling velocity (Richardson & Zaki 1954). The settling velocity can be described as the "hindered settling velocity". The simplest expression to describe "hindered settling velocity" was presented by Richardson & Zaki (1954). The settling velocity expression is shown in Equation 6 and is a function of porosity (or void ratio) and Stokes velocity:

$$v_s = v_{st} n^a = \frac{D_p^2 \left(\rho_s - \rho_w\right) g}{18\mu} \left(\frac{e}{1+e}\right)^a \qquad if\ e > e_s\ otherwise\ 0 \tag{6}$$

where v_s is hindered settling velocity (m/s), v_{st} is Stokes velocity (m/s), n is porosity, a is experimental parameter, D_p is effective particular diameter (m), ρ_s is density of solid particles (kg/m^3), ρ_w is density of fluid (kg/m^3), μ is mixture viscosity of fluid and solid particles (Pa.s), and e_s is critical void ratio or transitional void ratio when going from the sedimentation process to the consolidation process.

The settling velocity theory (Equation 6) assumes a uniform particle size distribution and is limited to laminar flow of small particle. It is assumed that the hindered velocity theory is applicable to oil-sands tailings deposition.

4.1 *Determination of parameters for Equation 6*

Four parameters (i.e. D_p, μ, a, and e_s) need to be determined when using Equation 6.

4.1.1 *Effective particle diameter, D_p*

One of the parameters central to the estimation of hindered velocity settlement is the effective particle diameter, D_p. The D_p parameter in the original formulation represented the diameter of uniform spherical particles involved in sedimentation. The original theory of sedimentation was based on the assumption that a group of particles were of uniform size. For materials such as soils it is necessary to estimate an "average" or "effective" particle diameter that can be applied to the sedimentation theory. The methods considered for the estimation of the D_p parameter in the present study are as follows:

- The D_p parameter can be assumed to be equal to the D_{10} of the grain-size distribution.

  The D_{10} of a particular grain-size distribution is known to provide a possible value against which the permeability of the soil can be correlated (Carrier III 2003). Therefore, D_{10} can be used as a first level approximation of the effective size for the D_p particle diameter.

- Using the size of flocculated groups of particles.

  Hindered settling may occurs as flocculating groups of very fine clays (i.e. floc size). There appears to be limited information in the literature regarding how best to estimate the floc size.

- Further literature review may be undertaken to ascertain the most appropriate way to use the grain-size distribution to calculate D_p.

4.1.2 *Mixture viscosity, μ*

The viscosity parameter, μ, has a significant influence on the settling rate. The mixture viscosity of the fluid and grains can be estimated using the following expression (Guth & Simha 1936)

$$\mu = \mu_0 \left[1 + \frac{2.5e}{1+e} + 14.1 \left(\frac{e}{1+e} \right)^2 \right] \tag{7}$$

where μ_0 = fluid viscosity = 1.02×10^{-3} Pa.s for water at normal temperature of 20 °C.

4.2 *Richardson & Zaki (1954) parameter, a*

The “*a*” parameter is empirical and can be determined experimentally. The valid range for the “*a*” parameter is considered to be between 2.5 to 5.5. If the effective grain size diameter is less than 0.01 mm, or if the particular Reynolds number is less than 1, then *a* is equal to 4.65. The “*a*” parameter is smaller when the average grain size is larger (Chapter 5, Winterwerp & van Kesteren 2004).

4.2.1 *Transitional void ratio, e_s*

The transitional void ratio, e_s, is the void ratio at which the dominating mechanism shifts from the sedimentation process to the consolidation process. The determination of such a void ratio is a matter of debate with respect to oil-sands tailings. There appears to be no definitive procedure for determining the transitional void ratio, e_s. One way to estimate e_s may be to quantify it as the void ratio corresponding to a small effective stress (e.g. 0.1 kPa to 0.5 kPa) on the soil compressibility curve. It is suggested that the selection of the transitional void ratio should be a topic for further evaluation and study. Pane & Schiffman (1985) suggested the following relationship for the estimation of e_s:

$$\frac{h_0}{1+e_0} = \frac{h_s}{1+e_s} \tag{8}$$

where h_0 is initial height, h_s is height of settlement interface at the transitional point from sedimentation to consolidation, and e_0 is initial void ratio.

These are the input parameters required for the coupled sedimentation and consolidation simulation.

5 COUPLED CONSOLIDATION AND CREEP PROCESS

Almost all soils exhibit some creep (Vermeer & Neher 1999). Creep is important in the later years (for instance during a period of 10 or 30 years) for problems involving large primary compression (Vermeer & Neher 1999). A classic example is the uneven settlement of the Leaning Tower of Pisa in Italy (Neher et al. 2003). Creep is also known as secondary compression/consolidation in many literatures (e.g. Bowles 1996). Secondary compression is part of the consolidation of that is observed after pore-water pressure ceases to change (Schrefler & Lewis 1998). Secondary compression represents the gradual readjustment of the soil particles to more stable equilibrium positions following the disruption caused by the effective stress increase and associated compression (Mesri & Castro 1987). The secondary compression behavior of soils is usually defined with the concept of C_α/C_c ratio. For a majority of inorganic soft clays, $C_\alpha/C_c = 0.04 \pm 0.01$ and for the highly organic plastic clays, $C_\alpha/C_c = 0.05 \pm 0.01$ (Mesri & Castro 1987). Secondary consolidation may be much more important where a very soft organic clay is under compression. Laboratory testing has shown that oil-sand fine tailings have a very high creep parameter. The ratio of C_α/C_c was found to be 0.085, which is high and comparable to other organic soils (Suthaker 1995). Suthaker (1995) argued that there can be significant creep taking place at the same time as primary consolidation in the case of tailing ponds because the depth of the fine tailings ranges from 40 to 60 m and ponds were filled fairly rapidly. The experimental study by the University of Alberta on 10 m standpipe tests on oil-sand tailings by Scott et al. (2004) and Jeeravipoolvarn et al. (2009) hypothesized that the reduction in volume under little or no effective stress may be caused by a creep mechanism. However, the implementation the creep models into consolidation models by Jeeravipoolvarn et al. (2008a) did not provide any favorable results.

The primary criticism of creep formulations is that they become a “dumping ground” for unexplained behavior. Creep mechanisms remain difficult to experimentally verify. Creep is also traditionally assumed to occur as a secondary mechanism in traditional soft soils. It has been suggested that creep must happen during primary and secondary consolidation in the case of oil-sand tailings.

The theory of modeling the creep in this study is based on the work of Nakai et al. (2013) and it assumes that the soil behaves as elasto-viscoplastic materials. The theory assumes that the incremental strain in normally consolidated soils will have two components, namely elastic and plastic strain (including creep) under any increase in stress. The increment in strain can be expressed in terms of void ratio.

The increment elastic strain is:

$$d\left(e\right)^{el} = \kappa \frac{d\sigma'}{\sigma'} \tag{9}$$

The increment plastic strain is:

$$d\left(e\right)^{pl} = \left(\lambda - \kappa\right)\left(1 - \frac{1}{s}\right)\frac{d\sigma'}{\sigma'} + \lambda_\alpha\left(1 - \frac{1}{s}\right)\frac{dt}{t} \tag{10}$$

where λ and κ are compression and swelling indices, λ_α is coefficient of secondary compression, and s is the parameter related to creep rate.

$$s = \frac{\left(e\right)_0^{pl}}{\lambda_\alpha} e^{\frac{F}{\lambda_\alpha}} + 1 \tag{11}$$

$$F = \left(\lambda - \kappa\right)\ln\frac{\sigma' + d\sigma'}{\sigma'} \tag{12}$$

where $\left(e\right)_0^{pl}$ is initial plastic strain rate and it can be determined using the Equation 13 with $t_{ref} = 1$ day.

$$\left(e\right)_0^{pl} = \frac{\lambda_\alpha}{t_{ref}} \tag{13}$$

Therefore, the total change in void ratio under an increment in effective stress, $d\sigma'$, is:

$$d\left(e\right) = d\left(e\right)^{el} + d\left(e\right)^{pl} \tag{14}$$

For large-strain consolidation with creep, the creep can be incorporated into Somogyi's formulation (1980) as follows:

$$\frac{\partial}{\partial z}\left[\frac{k}{\gamma_w(1+e)}\frac{\partial u}{\partial z}\right]+\frac{de}{dt}=0 \tag{15}$$

$$\frac{de}{dt}=\frac{1}{dt}\left[\kappa\frac{d\sigma'}{\sigma'}+(\lambda-\kappa)\left(1-\frac{1}{s}\right)\frac{d\sigma'}{\sigma'}+\lambda_\alpha\left(1-\frac{1}{s}\right)\frac{dt}{t}\right] \tag{16}$$

$$\frac{de}{dt}=\frac{d\sigma'}{dt}\frac{1}{\sigma'}\left(\lambda-\frac{\lambda}{s}+\frac{\kappa}{s}\right)+\lambda_\alpha\left(1-\frac{1}{s}\right)\frac{1}{t} \tag{17}$$

$$\frac{de}{dt}=-\frac{du}{dt}\frac{1}{\sigma'}\left(\lambda-\frac{\lambda}{s}+\frac{\kappa}{s}\right)+\lambda_\alpha\left(1-\frac{1}{s}\right)\frac{1}{t} \tag{18}$$

Equations 15 and 18 can be used to solve the large-strain consolidation with creep.

6 BENCHMARKING

The purpose of the benchmarking exercise is to apply large-strain consolidation theory coupled with sedimentation or creep to the standpipe experiments and determine whether they can provide a better match to the measured data.

6.1 *Standpipe 1*

6.1.1 *Material properties*

The material consists of oil-sands tailings taken from Syncrude's Mildred Lake Tailings Impoundment in 1982. It has a specific gravity of 2.28 and an initial void ratio of 5.17. The properties used in the large-strain consolidation are shown in Table 2. The curve fits to the effective stress – void ratio data by Power function (Equation 3) and Weibull function (Equation 4) are shown in Figure 1. Although both Power and Weibull functions closely fit to the measured data for the larger stresses, the Power function is unable to match the laboratory data if the effective stress is smaller than 0.2 kPa.

The same Power function parameters (*A* and *B*) for effective stress – void ratio relationship are used for coupled sedimentation and consolidation analysis. However, slightly different parameters were used for hydraulic conductivy, i.e. $C = 5.0 \times 10^{-6}$ m/day and $D = 3.507$. A slightly lower hydraulic conductivity has been used in order to match the settlement data. As mentioned in section 3, the measurement of hydraulic conductivity of fine tailings is challenging and the measured hydraulic conductivity data shows a spread of the data (e.g. Jeeravipoolvarn et al. 2008a). The hydraulic conductivity used for coupled sedimentation and consolidation is slightly close to the the lower bound as shown in Figure 2.

The sedimentation is included by considering the hindered settling velocity with following parameters for oil-sands tailings: effective particle diameter, $D_p = 0.47$ µm, mixture viscosity, $\mu = 103.68$ Pa.day, Richardson & Zaki parameter, $a = 4.65$, and transitional void ratio, $e_s = 4.394$. For coupled consolidation and creep simulation, the Weibull function parameters (*A*, *B*, *E*, and *F* in Table 2) are used for the effective stress – void ratio relationship. The parameters used for hydraulic conductivity are: $C = 6.91 \times 10^{-6}$ m/day and $D = 3.573$ as shown in Figure 2. The value of compression index was obtained from the compressibility curve Figure 1. The swelling index and secondary consolidation coefficient are determined using the following relationships:

$$\frac{\kappa}{\lambda} = 0.125 \tag{19}$$

$$\frac{\lambda_\alpha}{\lambda} = 0.05 \tag{20}$$

These ratios are based on the work of Mesri & Castro (1987) who recommended ratios κ/λ = 0.1 – 0.2 and λ_α/λ = 0.04 – 0.06.

Table 2. Modeling parameters for large-strain consolidation for standpipes 1 and 3 (Unit of effective stress = kPa and unit of hydraulic conductivity = m/day.

Relationship	Parameter	Standpipe 1	Standpipe 3
Effective stress – void ratio (Equation 3)	*A*	3.391	-
	B	-0.308	-
Effective stress – void ratio (Equation 4)	*A*	5.50	1.08
	B	4.97	0.77
	E	1.03	1.30
	F	-0.67	-0.29
Hydraulic conductivity – void ratio (Equation 5)	*C*	6.51×10^{-6}	2.76×10^{-3}
	D	3.824	3.824

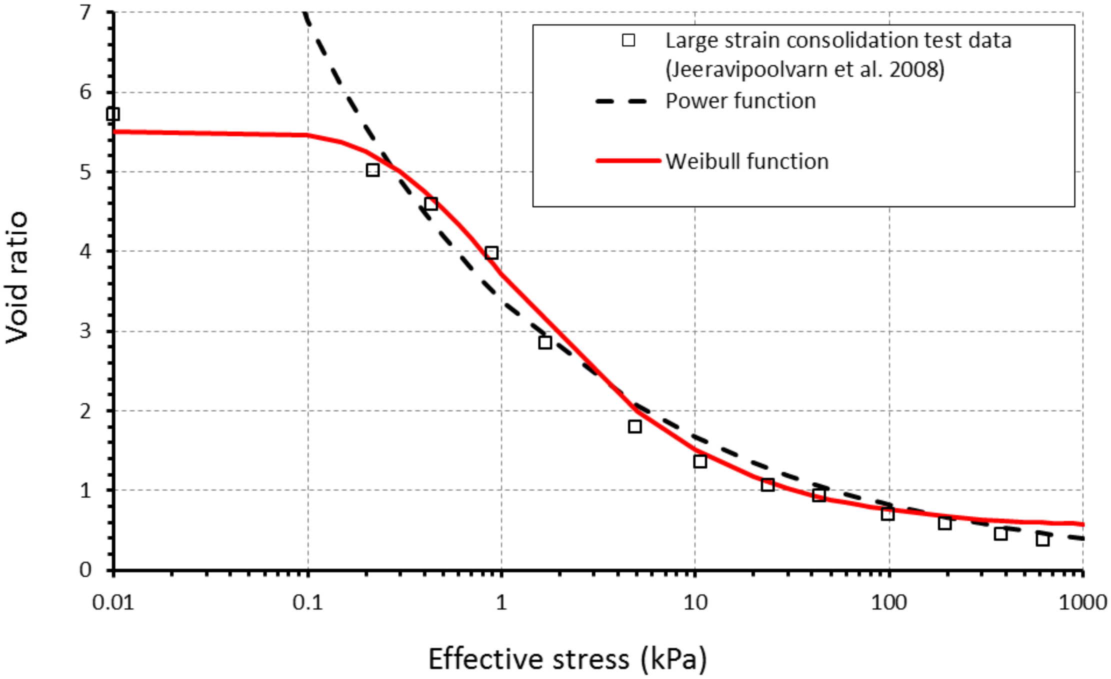

Figure 1. Compressibility of oil-sands fine tailings in Standpipe 1.

6.1.2 *Boundary conditions*

The initial head of 10 m is assumed. The upper boundary of the model is freely drained, i.e. satisfying the zero excess pore-water pressure at the top. The bottom of the model is impermeable for water flow and is restrained to move.

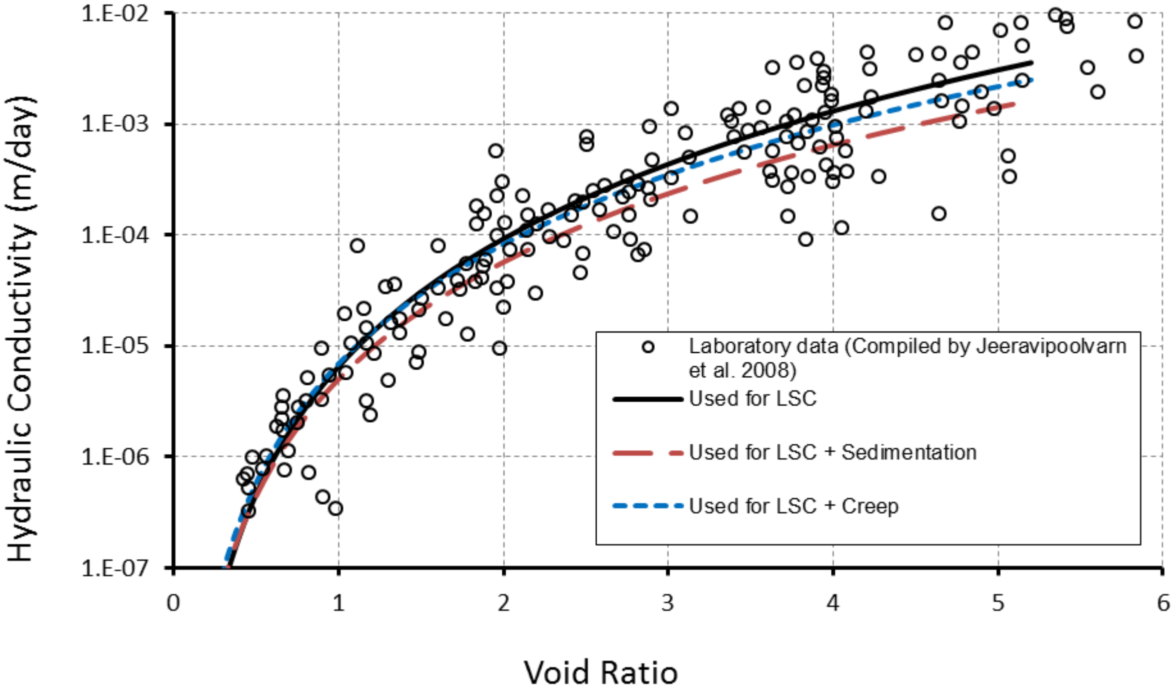

Figure 2. Hydraulic conductivity of oil-sands fine tailings in Standpipe 1.

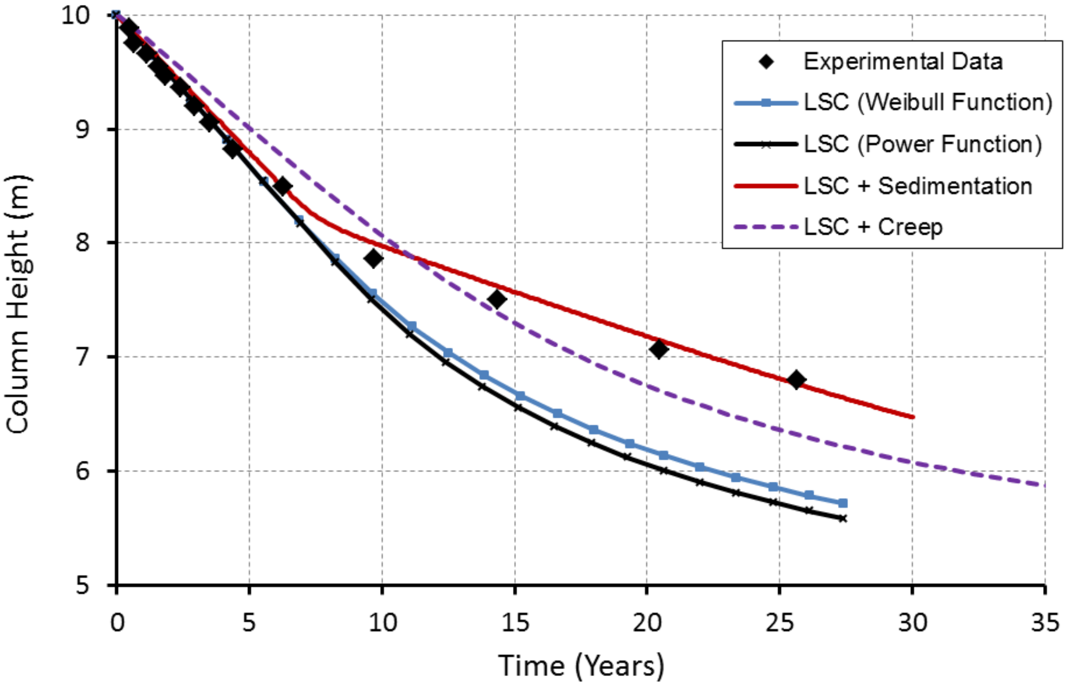

Figure 3. Surface settlement of Standpipe 1.

6.1.3 *Results*

Figure 3 compares the predicted settlements by applying three different theories to standpipe 1. It can be seen from Figure 3 that the large-strain consolidation largely overpredicts the surface settlement in the long-run. The Power function for effective stress – void ratio relationship predicts slightly larger consolidation than the Weibull function.

When the sedimentation is included, the prediction of settlement interface agrees very well with the experimental observation. However, it shows that the sedimentation process could last for up to 7 years, which may be questionable.

When the creep is included in the process, the simulation shows a sign of long term improvement, but does not fit as well in the short term. Determination of the creep parameters requires an effort as well.

6.2 *Standpipe 3*

6.2.1 *Material properties*

Standpipe 3 consists of oil-sands tailings mixed with cyclone tailings sand to increase the percent sand in the mixture to 82%. The specific gravity of the material is 2.58 and an initial void ratio is 0.87. The Weibull function (Equation 4) is used to fit effective stress – void ratio data and the Power function (Equation 5) is used for hydraulic conductivity – void ratio data. The parameters used in the large-strain consolidation are presented in Table 2.

6.2.2 *Boundary conditions*

The flux conditions consist of a constant head of 10 m at the top boundary and a zero flux boundary on the bottom of the column. This forces the water to flow from bottom out through the top boundary, while simulating a constant water table above the soil region. The deformation at the bottom is restrained.

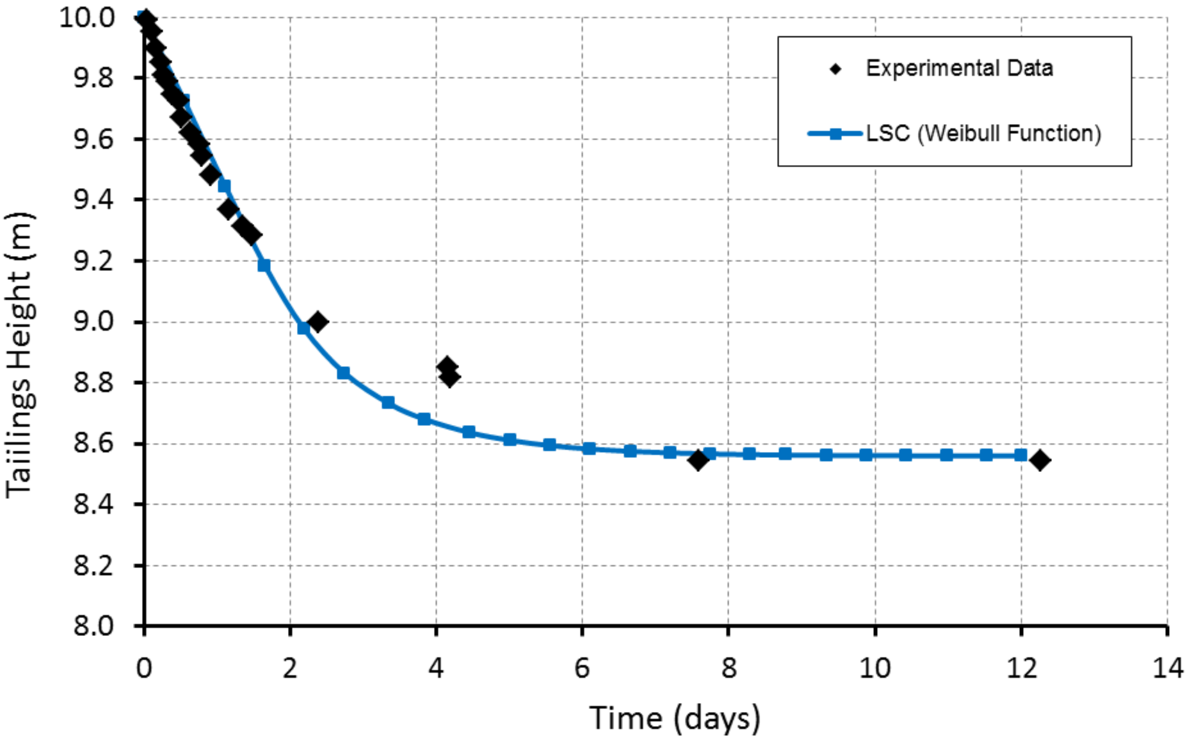

Figure 4. Surface settlement of Standpipe 3.

6.2.3 *Results*

As can be seen in Figure 4, the large-strain consolidation is able to predict the tailings surface settlement closely except that the prediction appears to consolidate faster in about year 4. This indicates that the materials in standpipe 3 can well be predicted well using large-strain consolidation theory only. It was reported that the significant amount of effective stresses have been developed in standpipe 3 during the consolidation (Jeeravipoolvarn et al. 2009). The large amount of effective stresses could be because of higher percentage of sand in standpipe 3, which makes it to behave as other normally consolidated soils.

7 CONCLUSIONS

The applications of large-strain consolidation, coupled consolidation and sedimentation, and coupled consolidation and creep have been examined in this study to benchmark the University of Alberta standpipe experimental results on oil-sand fine tailing and mix of materials. It was observed that where the generation of effective stress is normal during the consolidation settlement, the large-strain consolidation theory is able to predict the material behavior well. However, when the generation of effective stress and settlement relation is observed to be unusual, the application of consolidation theory coupled with sedimentation or creep process may provide some improvements in the predictions.

The following points can be concluded from the numerical predictions:

- Using sedimentation can match the behavior, but it may be difficult to accept that this process is happening over a long time.
- One difficulty in sedimentation process could be the estimation of transposal void ratio. One empirical approach is to estimate by trial and error. Theoretical approach of the estimation of the transitional void ratio would improve analysis in the future.
- Coupled sedimentation and consolidation may be possible to be utilized in certain scenarios.
- Using creep can improve the predictions, but there are difficulties in obtaining the material properties.
- Using creep has also difficulty in matching the initial dewatering behavior.

The study shows that it still has difficulty in understanding the mechanism of oil-sands fine tailings well and further research is needed on both processes.

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