Consolidation modeling of oil sands fine tailings: history matching

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ABSTRACT
The use of a finite strain consolidation theory to predict compression behaviour of oil sands fine tailings does not provide a good agreement with experimental data. To search for a possible explanation of this discrepancy, history matching was performed by three approaches namely a pre-consolidation, a creep compression and a hydraulic conductivity layering consolidation. Results indicate that the pre-consolidation and creep methods provide negligible improvement while the layering approach gives the best prediction not only for interface prediction but also for void ratio, excess pore pressure and effective stress profiles. Examination of modeling parameters suggests that the hydraulic conductivity increases upward. This led to a hypothesis that channeling might cause the deviation of the conduction property of the slurry. For this oil sands fine tailings, it is concluded that the conventional approach can lead to a large error, considerations of a pre-consolidation and creep compression do not improve prediction and a channeling phenomena could be a major reason of the discrepancy observed between the theory and the experiment.

RÉSUMÉ
L'utilisation d'une théorie finie de consolidation de contrainte de prévoir le comportement de compression des produits de queue fins de sables d'huile ne fournit pas à une bonne concordance des données expérimentales. Pour rechercher une explication possible de cette anomalie, l'assortiment d'histoire a été effectué par trois approches notamment une pré-consolidation, une compression de fluage et une consolidation posante de conductivité hydraulique. Les résultats indiquent que les méthodes de pré-consolidation et de fluage fournissent l'amélioration négligeable tandis que l'approche posante donne la meilleure prévision pas seulement pour la prévision d'interface mais également pour le rapport vide, pression excessive de pore et des profils efficaces d'effort. L'examen de modeler des paramètres suggère que la conductivité hydraulique augmente vers le haut. Ceci a mené à une hypothèse que creuser des rigoles pourrait causer la déviation de la propriété de conduction de la boue. Pour cette huile ponce les produits de queue fins, on le conclut que l'approche conventionnelle peut mener à une grande erreur, des considérations d'une pré-consolidation et la compression de fluage n'améliorent pas la prévision et les phénomènes creusants des rigoles pourraient être une raison importante de l'anomalie observée entre la théorie et l'expérience.

1 INTRODUCTION

In Northern Alberta, Canada, oil sands industries produce large volumes of tailings. For Syncrude Ltd. alone, there is currently 400 Mm^3 of fine tailings and this amount is growing. To manage the volumes effectively, engineers must be able to predict a rate of compression of these tailings. The geotechnical approach to predict consolidation behaviour of soft soils is to use a finite strain consolidation theory (Gibson et al. 1967). The theory is performed by using two important constitutive relationships which are effective stress - void ratio and hydraulic conductivity - void ratio relationships directly determined from a large strain consolidation test.

To verify the theory, experimental results from a ten meter high standpipe test filled with the fine tailings at the University of Alberta is used. The test was started in 1982 and it has been under monitoring for more than 20 years. This test result provides a great opportunity to model long term behaviour of the tailings. Results of a straight implementation of the theory and the constitutive relationships, however, do not provide a satisfying prediction having a large error of more than 30 percent of the experimental value. This disagreement between the theory and the experiment raises a question on the prediction capability of the theory. According to Krizek and Somogyi (1988), there are two choices for engineers to perform when this problem occurs, one is to perform a trial and error to find appropriate constitutive relationships for the problem and another is to research for missing physics and implement it into a model.

Some consolidation related phenomena that were reported and not originally included in the finite strain consolidation theory are segregation, channeling, creep, pre-consolidation and non-Darcian flow phenomena.

Segregation is referred to soil particle sorting; coarser/heavier particles slowly sink to the bottom of a settling volume and leave smaller/lighter particles suspended in the fluid. Segregation is not desired as the self-weight stresses are not effectively utilized. While segregation is important, the fine tailings contain approximately 95% fines therefore segregation effects are potentially negligible.

Compressibility and hydraulic conductivity of the fine tailings are shown in Figures 1 and 2 respectively. Figure 1 shows that the compressibility of the fine tailings is dependent on initial void ratio. This type of behaviour is similar to other findings (Imai 1981, Been and Sills 1981, Scully et al. 1984). It can also be observed that unlike normal slurry, compressibility of this tailings show pre-consolidation behaviour at a low effective stress of around 1 kPa. At higher effective stress, all the compressibilities start to converge around an effective stress of 10 kPa. It is noted that Scully et al. (1984) also found that the compressibility curves showed an apparent pre-consolidation effect in a range of effective stress of 1 kPa and above for phosphatic tailings and Sridharan and Prakash (1999) showed that montmorillonite clay behaves as an over consolidated soil in the low effective stress range of 0.25 to 0.8 kPa. Similar compressibility converging behaviour was shown by Myint et al. (2003) who suggested that the transition between ultra soft soils to Terzaghi soils is approximately at an effective stress of about 10 kPa.

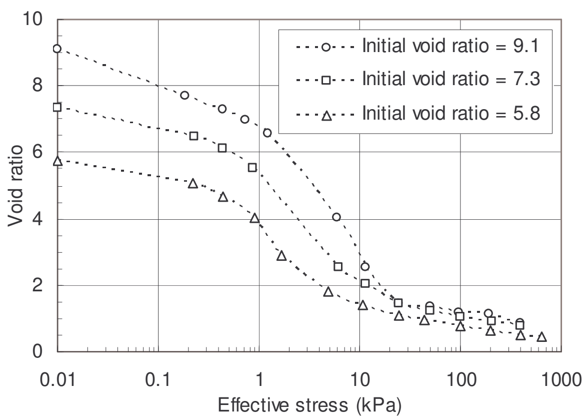

Figure 1. Compressibility of fine tailings (Suthaker 1995)

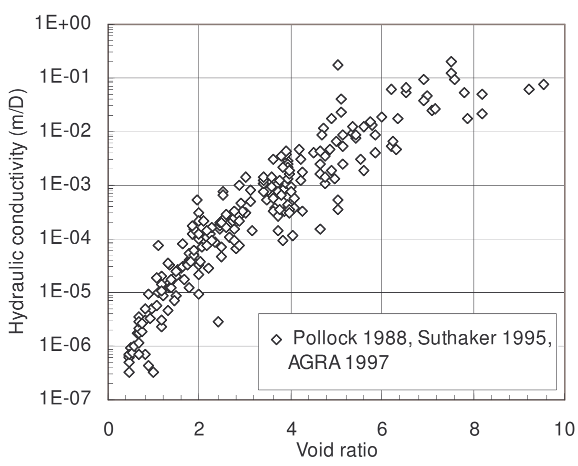

Figure 2. Hydraulic conductivity of fine tailings

Another factor that affects compressibility is time dependent behaviour or creep. Sill (1998) used X-ray density measurement coupled with pore pressure data to evaluate density with effective stress of various slurries and showed that compressibility of slurry is not uniquely determined. Later Bartholomeeusen et al. (2003) presented common overestimate predictions of initial settling rate by various consolidation models and pointed out that this was due to time or rate dependence of correlation between effective stress and void ratio. This is only partly true for slurry as the difference in compressibility will not alter the initial settling rate which is dominated by the hydraulic conductivity - void ratio relationship.

Nevertheless, the creep behaviour affects settlement prediction later on in the consolidation process specifically after the linear settling region. To be able to capture creep behaviour, it is suggested that the most appropriate way is to include time in the constitutive relation in a form of void ratio, effective stress and rate of compression (Bjerrum 1967, Leroueil et al. 1985, Kim and Leroueil 2001, Bartholomeeusen 2003). The first implementation of creep behaviour in slurry consolidation modeling was fulfilled by Bartholoeeusen (2003) who proposed a compressibility surface in a form of e, σ' and $\dot{e}$ for slurry. This concept was originated from Bjerrum (1967) and Leroueil (1985) and the difference is that a compressibility surface function and a fluid dynamic formulation are used by Bartholomeeusen (2003). A prediction of interface settlement by the creep model showed a good agreement with experimental data.

In Figure 2, hydraulic conductivity measurements of the fine tailings from various sources indicate that this material is low in hydraulic conductivity and there is a considerable spread of the data. Part of this is due to the non-Darcian behaviour of this material as the hydraulic conductivity is dependent on the hydraulic gradient; a higher hydraulic gradient results in a lower hydraulic conductivity (Suthaker and Scott 1996). Therefore test data with different hydraulic gradients give rise to the discrepancy and it was suggested by Suthaker and Scott (1996) that for modeling purposes hydraulic conductivity measurement should be performed at the same hydraulic gradient in the field.

Hydraulic conductivity value can also be affected by channeling. Several researchers have reported flow channels (Been and Sills 1981, Caughill 1992, Tang 1997, Edil and Fox 2000). Edil and Fox (2000) discussed that this dewatering structure is a localized macro-structural feature resulting from a preferential flow path and when this is observed the assumption of uniform pore fluid migration may not be appropriate for consolidation theories. Edil and Fox (2000) also showed that subjective interpretation of the dewatering structure indicates no obvious pattern or distribution which suggests a random phenomenon. One would expect that pore fluid has a high tendency to flow through these channels rather than the soil matrix.

Given the complex phenomena and large discrepancy between experiment and theoretical prediction on oil sands fine tailings, this article presents historical consolidation analyzes of this tailings based on different approaches. Emphasis of this study is on modeling by the conventional theory, pre-consolidation compressibility, a creep compression and layering effects on hydraulic conductivity. Modeling of the four approaches were performed separately and the results were interpreted to bring an insight view of what might be the crucial mechanics controlling compression behvaiour of this class of material.

2 CONSOLIDATION MODELS

This section provides assumptions and executions of each consolidation modeling approach including the conventional finite strain consolidation analysis, pre-consolidation behaviour analysis, creep compression analyses and layering consolidation analysis.

2.1 Conventional Finite Consolidation Analysis

Two approaches are performed and they are the conventional finite strain consolidation analysis with and without adjusting constitutive relationships. The two constitutive relationships are effective stress - void ratio and void ratio - hydraulic conductivity relationships shown as Equations 1 and 2 respectively. It is assumed that experimentally determined relationships give the best representation of the material consolidation behaviour.

$$e = A\sigma'^{B} \qquad [1]$$

$$k = Ce^{D} \qquad [2]$$

Where σ' is effective stress, k is hydraulic conductivity, e is void ratio and parameters A, B, C and D are laboratory determined parameters. With Equation 1 and 2, the finite strain consolidation equation (Somogyi 1980) for quiescent condition is expressed as Equation 3. Where u is excess pore pressure and z is material coordinate.

$$\frac{\partial u}{\partial t} + \frac{\sigma'^{(1-B)}}{AB\gamma_w}\left(\frac{k}{1+e}\right)\frac{\partial^2 u}{\partial z^2} + \frac{\sigma'^{(1-B)}}{AB\gamma_w}\frac{\partial\left(\frac{k}{1+e}\right)}{\partial z}\frac{\partial u}{\partial z} = 0 \qquad [3]$$

2.2 Pre-Consolidation Behaviour Analysis

According to considerable evidence (Suthaker 1995, Pollock 1988) from large strain consolidation tests, the compressibility of this material exhibits pre-consolidation behaviour. This behaviour makes the use of the power law function [1] questionable and the use of a Weibull function [4] is employed for this study as this function can capture the pre-consolidation behaviour and gives a better coefficient of determination. For the hydraulic conductivity - void ratio relationship, the power law is still appropriate.

$$e = A - B.\exp[-E.\sigma'^{F}] \qquad [4]$$

In equation [4], A, B, E and F are laboratory determined parameters. The modified finite strain consolidation equation with Equation 4 is expressed as Equation 5.

$$\frac{\partial}{\partial z}\left[\frac{-k(e)}{\gamma_w(1+e)}\right]\frac{\partial u}{\partial z} + \frac{-k(e)}{\gamma_w(1+e)}\frac{\partial^2 u}{\partial z^2} + B.E.F.\exp[-E.\sigma'^{F}].\sigma'^{(F-1)}\frac{\partial u}{\partial t} = 0 \qquad [5]$$

2.3 Creep Compression Analysis

In this paper, creep is assumed to have two modes which are based on two similar concepts. The first one is called creep type 1 which is creep behaviour that occurs independently to consolidation. This type of creep is based on compression behaviour observation of the fine tailings in both field and laboratory. Detailed philosophy of this compression mode can be found elsewhere (AGRA 1997). Therefore total deformation is a combination of independent creep compression and consolidation. A creep function is postulated and it is expressed as Equation 6.

$$\dot{e} = M.\exp[e.N] \qquad [6]$$

Where M and N are experimentally determined parameters. This creep function is fitted from experimental data of creep rates versus void ratio.

A flow chart of creep type 1 analysis is illustrated in Figure 3. The analysis is performed by explicitly combining creep deformation (Δe_{cr}) to consolidation deformation (Δe_{con}) at the end of each time step (Δt) of the numerical solution. As this will cause an incompatibility of compressibility, it must be adjusted to follow the resulted deformation.

The second mode, creep type 2, is based on a concept of strain rate presented by Leroueil, (1985). Creep type 2 is performed by assuming a constitutive relationship in a form of $e = f(\sigma', \dot{e})$. A form of a function used to combine rate of compression and compressibility is selected as Equation 7 where G, H, I and J are experimental determined parameters and A is from Equation [1]. This relationship is assumed to exist and available experimental data are used to obtain parameters in the relationship.

$$A = G - H.\exp[-I.\dot{e}^{J}] \qquad [7]$$

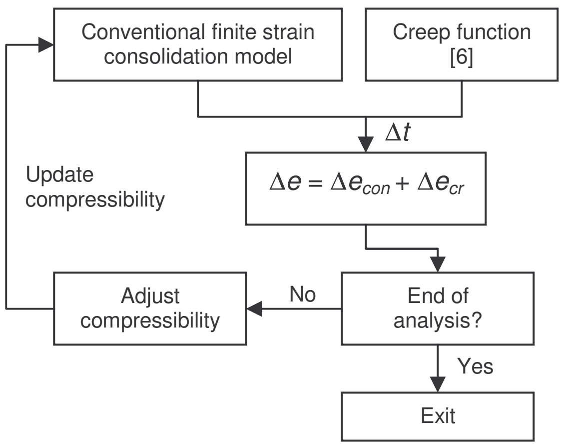

Figure 3. A computational scheme of creep type 1

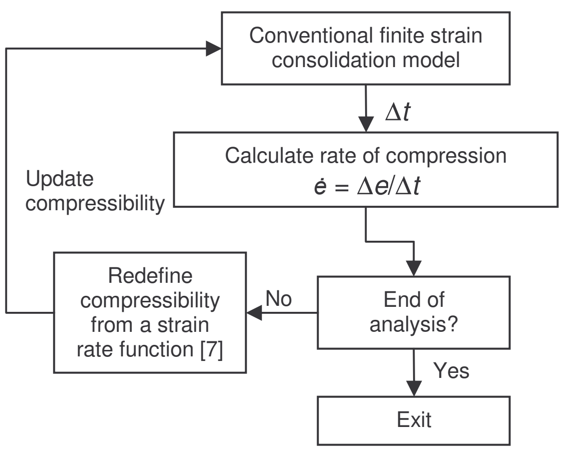

Figure 4. A computational scheme of creep type 2

A flow chart of creep type 2 analysis is shown in Figure 4. The analysis is performed by calculating $\dot{e}$ and subsequently redefining soil compressibility based on $\dot{e}$ data. As a new compressibility is obtained based on the void ratio rate correlation, a next time step is performed until the end of a specified simulation period.

2.4 Layering Consolidation Analysis

A channeling or dewatering structure is observed as discussed in Section 1. Observations suggest that channeling occurs due to boiling; a condition where the effective stress is lower than the seepage stress. As this is localized and randomly occurred it is not currently possible to quantify this effect. In order to continue this investigation, a first assumption is drawn that channeling occurs homogeneously in a horizontal plane and therefore it is a one dimensional (vertical) effect. This is persuasive according to 3*D* reconstruction of channeling (Edil and Fox 2000). Conceivably, the channels will act as a dewatering structure that drains off the excess pore pressure to the surface of tailings. Therefore the occurrence of the channels would increase hydraulic conductivity locally. This leads to a second assumption that hydraulic conductivity is varied vertically due to channeling. As self-weight consolidation advances upward for a single drainage boundary condition, the development of effective stress would likely shutoff the boiling process and the subsequently settlement would seal off the drainage structure resulting in the hydraulic conductivity increasing upwards. Given the large variability of measured hydraulic conductivity in Figure 2, a last assumption is given that the hydraulic conductivity is lowest at the bottom and gradually increases to higher values at higher elevations. Boundaries of the hydraulic conductivity are chosen from the available data in the following section.

3 MODELING PARAMETERS

An implicit finite difference method was chosen to solve all governing equations numerically due to its stability. Numerical parameters used in this paper are $\Delta z = z/200$, $\Delta t = 0.1$ for spatial and temporal resolutions. Initial conditions and soil parameters of the fine tailings in the verification standpipe are an initial height of 10m, an initial solids content of 30.6% (e = 5.17, w = 227%) and a specific gravity of 2.28. Modeling parameters of approaches 2.1 to 2.3 are listed in Table 1.

Table 1. Modeling parameters (units in kPa, m/D)

Parameters	Conventional	Pre-consolidation	Creep type 1	Creep type 2
A	3.391	5.504	3.391	3.391
B	-0.308	4.974	-0.308	-0.308
C	6.510×10^{-6}	6.510×10^{-6}	6.510×10^{-6}	6.510×10^{-6}
D	3.824	3.824	3.824	3.824
E	-	1.031	-	-
F	-	-0.674	-	-
G	-	-	-	2.823
H	-	-	-	1.033
I	-	-	-	1.249×10^{3}
J	-	-	-	1.218
M	-	-	9.195×10^{-11}	-
N	-	-	3.798	-

The conventional modeling parameters are obtained by using a power law on compressibility and hydraulic conductivity in Figures 5 and 6. The pre-consolidation model uses a Weibull function instead of a power law for compressibility (Figure 5). Creep models use the same compressibility and hydraulic conductivity to the conventional model with additional creep functions. Creep type 1 parameters (*M*, *N*) are obtained by best fitted on experimental creep data (Figure 7) by Equation 6 and creep type 2 parameters (G, H, I, J) are arbitrary chosen based on compressibility and strain rate relations (Figure 8) of the fine tailings given by Jeeravipoolvarn (2005).

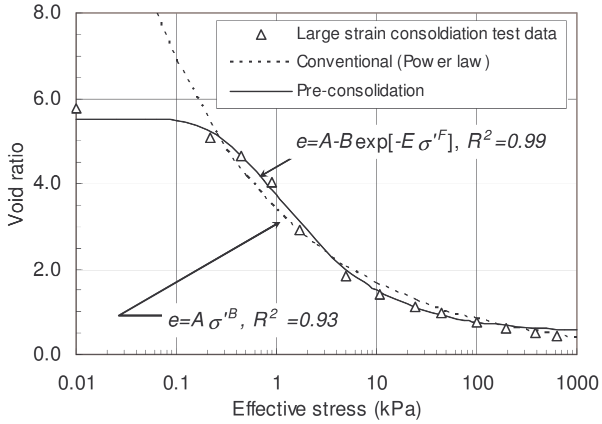

Figure 5. Compressibility of fine tailings

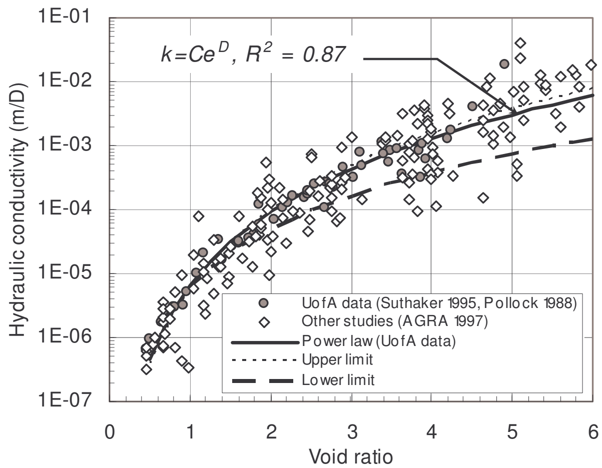

Figure 6. Hydraulic conductivity of fine tailings

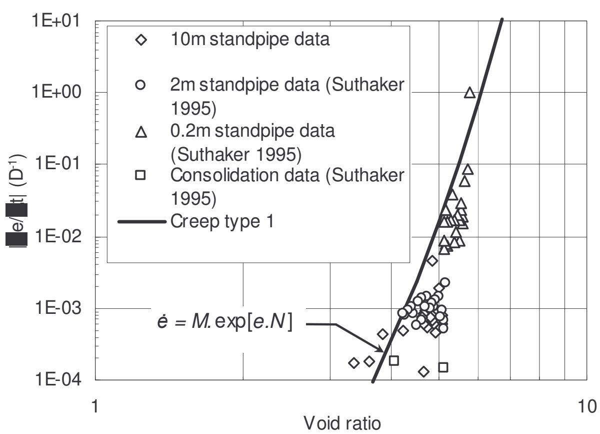

Figure 7. Creep rate vs. void ratio of fine tailings

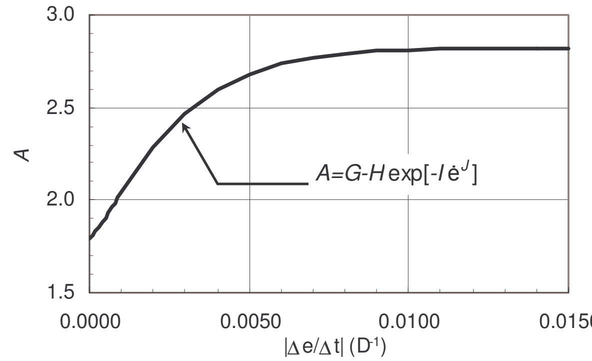

Figure 8. Creep rate vs. compressibility parameter A

For the layering consolidation analysis, the hydraulic conductivity parameter D of the soil layers is assumed to range between the upper and lower limits of the experimental data in Figure 6. The upper and lower limits are assumed to represent maximum channeled system and homogenous system respectively. An arbitrary distribution of the hydraulic conductivity parameter D is selected for optimum history matching and the distribution is plotted against normalized height, H/Ho, in Figure 9.

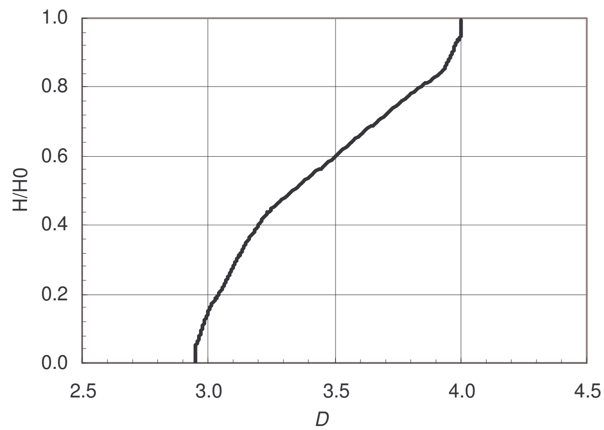

Figure 9. Hydraulic conductivity parameter D vs. H/Ho

4 MODELING RESULTS

Tailings-water interface measurement is shown with all simulation results in Figure 9. Comparisons of experimental measurement of void ratio profiles, excess pore water pressure profile and effective stress profiles with numerical predictions are shown in Figures 10, 11 and 12 respectively. Elapsed times of 2 days, 10 years and 20 years are chosen for the profile comparisons while experimental data and predictions for other elapsed time fall between these numbers.

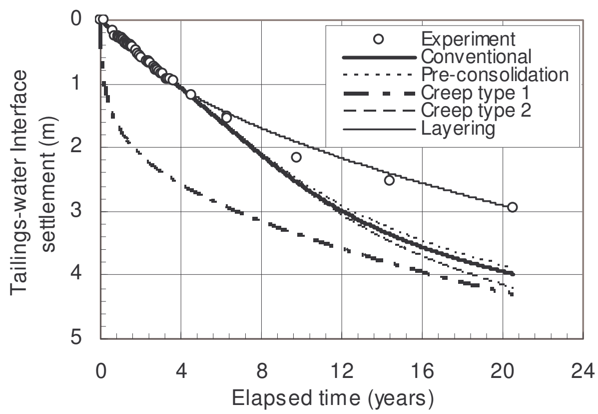

Figure 10. Tailings water interface settlement comparison

It is shown by the interface settlement comparison (Figure 10) that the conventional finite strain consolidation theory with assigned power law functions to compressibility and hydraulic conductivity is able to capture the interface settlement up to about 4 years but fail to capture further interface settlement data of the fine tailings with an overestimation error of 33% at 21 years. The profile comparisons of this model are shown in Figures 11(a), 12(a) and 13(a). The results indicate that none of the profiles are in good agreement. These disagreements led to extensive investigations of other possible mechanisms affecting the compression behaviour of the fine tails (Banas 1991, Suthaker 1995, Tang et al. 1997, AGRA 1997, Jeeravipoolvarn 2005).

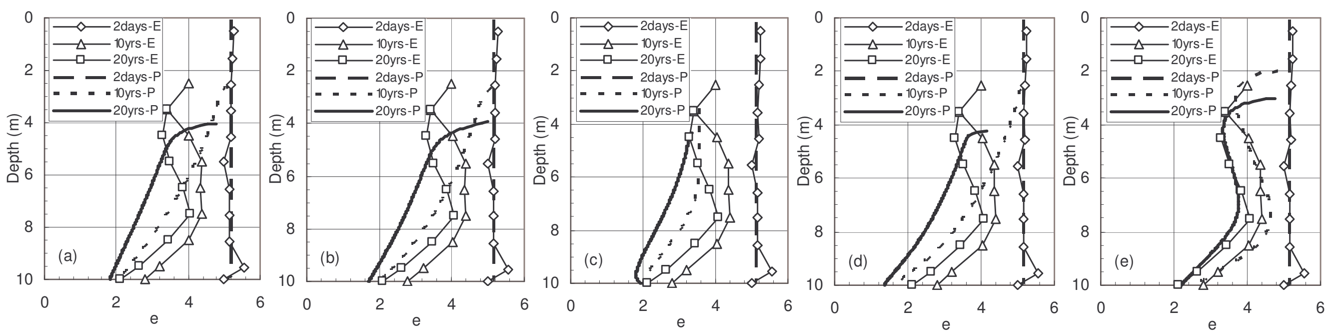

Figure 11. Void ratio comparison (a) conventional (b) pre-consolidation (c) creep type 1 (d) creep type2 (e) layering

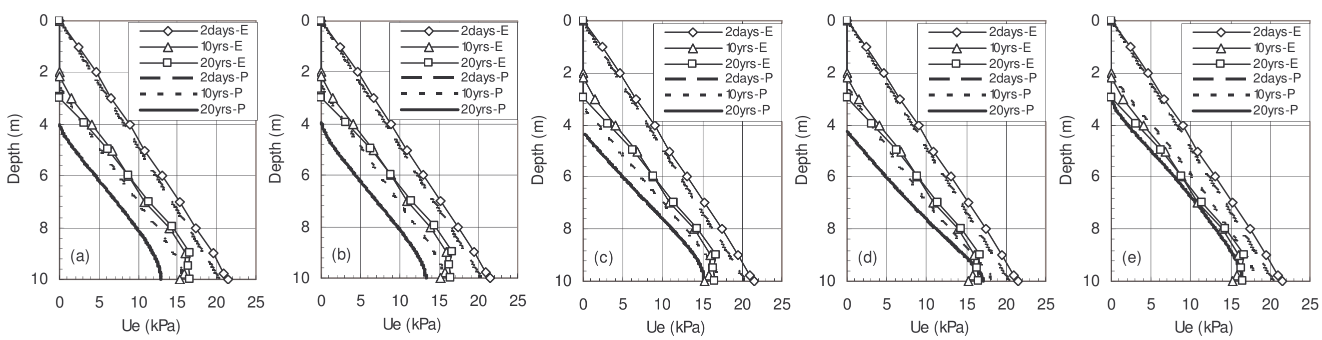

Figure 12. Excess pore water pressure comparison (a) conventional (b) pre-consolidation (c) creep type 1 (d) creep type2 (e) layering

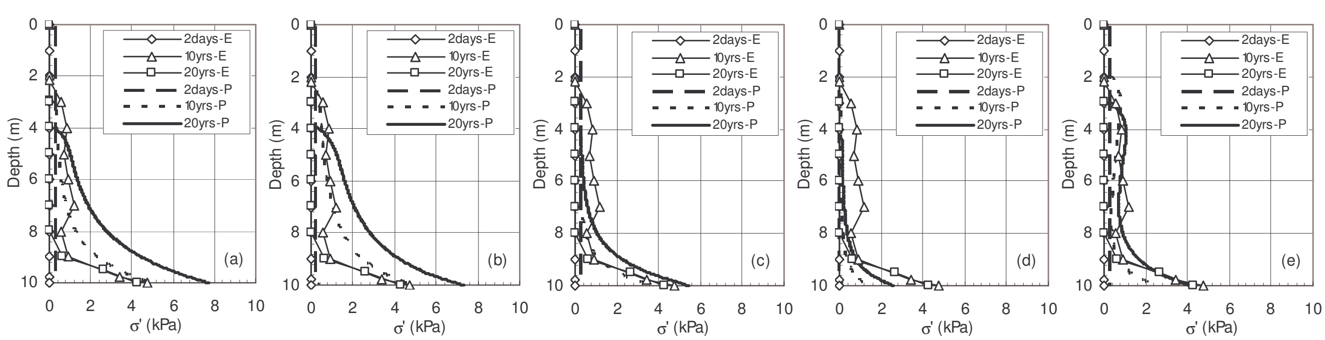

Figure 13. Effective stress comparison (a) conventional (b) pre-consolidation (c) creep type 1 (d) creep type2 (e) layering

Believed to be caused by a high thixotropy gain in strength of the fine tailings, the pre-consolidation compressibility approach even though it contains a considerably better compressibility function (higher coefficient of determination) only gives a slight improvement of the interface settlement prediction (Figure 10). Figures 11(b), 12(b) and 13(b) show that the pre-consolidation approach is not significantly different to the conventional approach. Given that the initial void ratio is 5.17, there certainly is a small over-consolidation pressure to overcome by self-weight stresses (Figure 1).

The creep type 1 interface prediction gives a large deviation from the experimental data. The void ratio profiles (Figure 11(c)) give an intriguing reduction in void ratio where there is no consolidation similar to experimental observations. These are however not unexpected as the additional strain was introduced by creep Equation 6. Nevertheless, creep type 1 is unable to capture experimental data in all aspects giving that the hydraulic conductivity is unchanged. According to AGRA (1997), an improved prediction can be obtained when a lower bound hydraulic conductivity is implemented with creep type 1.

Rate dependent compressibility, the creep type 2, gives a good agreement of interface prediction to about 4 years similar to the conventional approach while the prediction starts to diverge greater than the conventional method after 10 years (Figure 10). The effective stress and excess pore pressure responses at the 20 year prediction appear to be closer to experimental data however this is not to be deceiving as the interface error is larger than the conventional approach.

Considering a creep mechanism, the compressibility of soils is likely greater due to the viscous response as the duration of consolidation increases. This conflicts with the philosophy of thixotropy gain in strength behaviour where it is assumed that the pre-consolidation is caused by increasing undrained shear strength due to the development of gel structure with time. Sills (1998) and Barthomeeusen (2003) showed measurement of effective stress response with time for various slurries and from their experimental data it can be concluded that viscous response significantly makes slurry more compressible with time. According to Leroueil (1985), the magnitude of pre-consolidation pressure is a consequence of compression rate. This is consistent with the compressibility data of the fine tailings in Figure 1. As a higher initial void ratio with the same sample thickness implies a relatively higher rate of compression compared to a lower void ratio, the higher pre-consolidation pressure belongs to the higher initial void ratio. Therefore, it is concluded that for oil sands fine tailings, the cause of the apparent pre-consolidation pressure remains unknown but the magnitude of it is potentially related to the rate of compression. The influence of the pre-consolidation on compression behaviour is small and by considering a creep mechanism, it is conceivably negligible.

The layering approach interface prediction shown in Figure 10 indicates good history matching results. Shape and location of void ratio measurements are in good agreement with predicted profiles (Figure 11(e)). Excess pore pressure and effective stress predictions are also in a good agreement with experimental data (Figures 12(e) and 13(e)). Considering two thirds of the effective stress measurement data from the top of the compressing volume, this history matching slightly overestimates the effective stress data. At this location, there appears to be a reduction in void ratio without considerable effective stress development. As the layering approach neglects creep compression, a slight disagreement is expected. The different is small in a range of 1 to 2 kPa.

The approaches in this paper can be divided into two main parts which are compressibility approaches (Sections 2.2 and 2.3) and hydraulic conductivity approach (Section 2.4). It is arguable that both factors coexist during compression of slurry. While this is true, it must be stressed that the compressibility function does not have a large influence on the settlement prediction especially during the early stage (high void ratio stage) because of the low effective stresses in the slurry. The outcomes of all numerical simulations reinforce the great importance of hydraulic conductivity on the oil sands fine tailings compression behaviour. The discrepancy between experimental data and theoretical prediction likely involves mechanisms that affect hydraulic conductivity more than affecting the compressibility.

5 DISCUSSION AND CONCLUSIONS

It should be emphasized that the observed behaviour of both channeling and reduction in void ratio without gain in effective stress is not common only to the oil sands fine tailings but also appear in other types of slurries and tailings. History analyses were performed in this study giving intriguing hypotheses that might improve our understanding of slurry compression.

Two main simulation approaches were presented; compressibility and hydraulic conductivity approaches. The compressibility approach includes pre-consolidation and creep compression. The hydraulic conductivity approach refers to the layering mechanism that causes deviations in vertical hydraulic conductivity.

The pre-consolidation behaviour found in the compressibility of the oil sands tailings is believed to be caused by thixotropic gain in strength. In this study the pre-consolidation behaviour is modeled by a Weibull compressibility function which is found to be a more appropriate form of compressibility for the tailings compared to the conventional power law. Results from this approach give a slight improvement of interface settlement prediction. Void ratio, effective stress and excess pore pressure profile predictions however show a negligible advantage of this method.

For the creep compression approaches, both creep type 1 and type 2 increase deformations with time due to a viscous effect. As a result, the interface prediction with creep further overestimates the measured interface settlement data.

Creep type 1 is found to be able to produce a similar behaviour as in the experimental data where there is a reduction of void ratio with no effective stress development. However given that the interface prediction has a large error and the additional deformation is unjustified as some of it is already embedded in the compressibility, this method requires further investigation.

It is concluded that without any consideration of changes in hydraulic conductivity, all compressibility approaches are not able to provide better predictions compared to the conventional approach.

While the compressibility approaches are not promising, the layering approach or hydraulic conductivity approach gives reasonable history matching in all aspects. The important feature of reduction in void ratio under low effective stresses is also captured similar to creep type 1. Although the selected hydraulic conductivity parameters fall within the measured hydraulic conductivity data, a critical assumption drawn for this approach, that the dewatering structure increases hydraulic conductivity upward, is yet to be validated. Other possible mechanisms that affect micro and macro structures and therefore hydraulic conductivity of the slurry, such as thixotropy and non-Darcian flow behaviour, are also possible explanations. Further investigation on such phenomena is required to extend the current stage of understanding.

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