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Estimating Saturated Hydraulic Conductivity from Compression Curves for Fluid Fine Tailings

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ABSTRACT

The hydraulic conductivity – void ratio function of oil sands fluid fine tailings (FFT) is a critical parameter to the performance of tailings management plans, and strongly influences how soon tailings deposits will be ready for reclamation. Unfortunately, determination of field applicable hydraulic conductivity functions for fluid fine tailings is challenging. This paper considers estimation of the hydraulic conductivity function from the more easily determined compressibility function. Many researchers have correlated the consolidation stress *σ'*, void ratio *e* and saturated hydraulic conductivity *k* with easily attainable index properties (e.g. consistency limits, density, grain size distribution curves various types of soil. Previous work showed that such methods do not predict the hydraulic conductivity at higher void ratios with sufficient accuracy. This paper examines and assesses the predictability of the hydraulic conductivity function from the compressibility function using regression models, and also examines how such regression models can be improved by the use of single measured value of hydraulic conductivity. Analyses of a large database of FFT and amended FFT shows that the strategy of including one measured value of hydraulic conductivity substantially improves the predictive power of such regression models. A hypothetical large strain consolidation prediction is included to help quantify the relatively accuracy of the regression models.

RÉSUMÉ

Le rapport entre la conductivité hydraulique et le taux de vide des résidus fins de fluides des sables bitumineux est un paramètre essentiel à la performance des plans de gestion des résidus et influence fortement la rapidité avec laquelle les résidus seront prêts à être remis en état. Malheureusement, la détermination des fonctions de conductivité hydraulique applicables sur le terrain pour les résidus fins fluides est difficile. Cet article considère l'estimation de la fonction de conductivité hydraulique à partir de la fonction de compressibilité plus facilement déterminée. De nombreux chercheurs ont corrélé la contrainte de consolidation σ ', le taux de vide e et la conductivité hydraulique saturée k avec des propriétés d'indice facilement atteignables (par exemple limites de consistance, densité, courbes granulométriques) et la distribution granulométrique de différents types de sol. Des travaux antérieurs ont montré que ces méthodes ne prédisent pas la conductivité hydraulique à des taux de vide plus élevés avec une précision suffisante. Cet article examine et évalue la prévisibilité de la fonction de conductivité hydraulique à partir de la fonction de compressibilité en utilisant des modèles de régression, et examine également comment de tels modèles de régression peuvent être améliorés en utilisant une seule valeur mesurée de conductivité hydraulique. Les analyses d'une grande base de données de FFT et de FFT modifiée montrent que la stratégie consistant à inclure une valeur mesurée de conductivité hydraulique améliore sensiblement le pouvoir prédictif de tels modèles de régression. Une prévision hypothétique de consolidation de grandes souches est incluse pour aider à quantifier la précision relative des modèles de régression.

1 INTRODUCTION

Large volume of tailings produced as a by-product of mining operations in Northern Alberta poses a major environmental challenge for the mining industry in Northern Alberta. These materials consist of sand, silt, clay and a small fraction of residual bitumen and upon deposition they start to segregate; coarser fraction settling at the bottom forming beaches and dykes whereas the finer fraction of the material along with residual bitumen flow into the pond. This finer fraction, or fluid fine tailings (FFT) has been observed to stabilized at the water contents well above their liquid limits for decades (Chalaturnyk, Don Scott, & Özüm, 2002; Kasperski, 1992; MacKinnon, 1989).The slow dewatering behaviour of FFT can be associated with their poor consolidation properties; these materials have low hydraulic conductivity and demonstrates high thixotropic strength (Banas, 1991; Burchfield & Hepler, 1979; Ignasiak, Kotlyar, Longstaffe, Strausz, & Montgomery, 1983; Kessick, 1978; Van Olphen, 1964). From an operational standpoint, the disposal management of these materials become a challenge for the operators and in order to satisfy environmental protection requirements, an assessment of consolidation behaviour is essential (Jeeravipoolvarn, 2010; Znidarčić, Miller, van Zyl, Fredlund, & Wells, 2011).

Consolidation parameters, especially hydraulic conductivity (k), are highly variable and determining these parameters for FFT can be a difficult process as it requires large number of time-consuming or expensive field and laboratory tests. On the other hand, determining the compressibility curve is substantially less time consuming and easier to assess. There are number of predictive models available in the literature to estimate these highly variable parameters using easily measurable index properties which do not require the determination of the compressibility function (Berilgen, Berilgen, & Ozaydin, 2006; Chapuis & Aubertin, 2003); however, they are also proven to be not sufficiently accurate to predict hydraulic

Table 1: Summary of data sets utilized in this study

Untreated FFT	LL-PL	Consolidation Method	%clay-sand	Reference
SS 20%	60-35	Slurry Consolidometer	55-3	Suthaker (1997)
SS 25%	50-27	Slurry Consolidometer	55-3	Suthaker (1997)
SS 30%	40-20	Slurry Consolidometer	47-8	Suthaker (1997)
Tailings Sludge	41-19	Slurry Consolidometer	92-8	Pollock (1988)
OSFT	41-20	Falling Head Method	52-5	Owolagba (2013)
Ore A Type 1	49.5-25.8	Slurry Consolidometer	43-15	Miller (2010)
Ore A Type 2	59.6-30.5	Slurry Consolidometer	47-10	Miller (2010)
Ore B Type 4	52.1-26.9	Slurry Consolidometer	49-10	Miller (2010)
Ore B Type 5	58.3-29.1	Slurry Consolidometer	48-8	Miller (2010)
Standpipe 1	46-21	Slurry Consolidometer	50-5	Jeeravipoolvarn (2005)
COF 2008	43-18	Large Strain Consolidation Test	30-12	Jeeravipoolvarn (2010)
MFT Slurry	55-28	Calculated from Settling Curves	(45-50) - (7-10)	Yao (2016)
FFT	50-21	Large Strain Consolidation Test	15-4	Wilson, Kabwe, Beier, and Scott (2017)
Amended FFT				
Sludge-sand (46%)	41-19	Slurry Consolidometer	54-46	Pollock (1988)
Sludge-sand (80%)	41-19	Slurry Consolidometer	20-80	Pollock (1988)
Sludge-CaCl mix	41-19	Slurry Consolidometer	27-73	Pollock (1988)
Ore A Type 3	53.8-28.5	Slurry Consolidometer	43-15	Miller (2010)
Ore B Type 6	58.3-29.1	Slurry Consolidometer	49-10	Miller (2010)
East pond ILTT	58-24	Large Strain Consolidation Test	30-18	Jeeravipoolvarn (2010)
West pond ILTT	70-23	Large Strain Consolidation Test	48-18	Jeeravipoolvarn (2010)
Lab ILTT	66-23	Large Strain Consolidation Test	N/A	Jeeravipoolvarn (2010)
0.5% SAP treated	51.2-37.2	Constant Head Test	19-4	Farkish and Fall (2013)
1% SAP treated	51.2-37.2	Constant Head Test	19-4	Farkish and Fall (2013)
3% SAP treated	51.2-37.2	Constant Head Test	19-4	Farkish and Fall (2013)
TT1	28-18	Large Strain Consolidation Test	18-46	Wilson et al. (2017)
TT2	28-18	Large Strain Consolidation Test	17-46	Wilson et al. (2017)
TT4	25-17	Large Strain Consolidation Test	14-49	Wilson et al. (2017)
TT5	25-17	Large Strain Consolidation Test	14-49	Wilson et al. (2017)

conductivity at high void ratios, for purposes of design of deep oil sands tailings deposit.

Babaoglu and Simms (2017) have established that some predictive models provided an acceptable prediction for lower void ratios for oil sands tailings. However, the error between predicted and measured became greater than an order of magnitude for void ratios above 2, for about 50% of the samples. This difference is sufficient to result in substantial variance in predictions of consolidation time, in the order of hundreds of years, for deep deposits (>10 m in height) of tailings.

The objective of this paper is to investigate the use of other methods to estimate the void ratio (e) - hydraulic conductivity (k) relationship using:

i) the compressibility curve, and

ii) the compressibility curve along with a single hydraulic conductivity measurement in the higher void ratio

iii) Seeing how the accuracy of the previously developed predicted methods could be improved by a single measurement of k_{sat} at high void ratio.

The compressibility curve can be obtained relatively quickly compared to the hydraulic conductivity function, as its determination requires only paired measurements of density and pore-water pressure.

2 THE DATA SETS

The data used in this study includes 28 sets of hydraulic conductivity and compressibility curves of either FFT or amended FFT. The names, original source, Atterberg limits, and consolidation method, is given in Table 1.

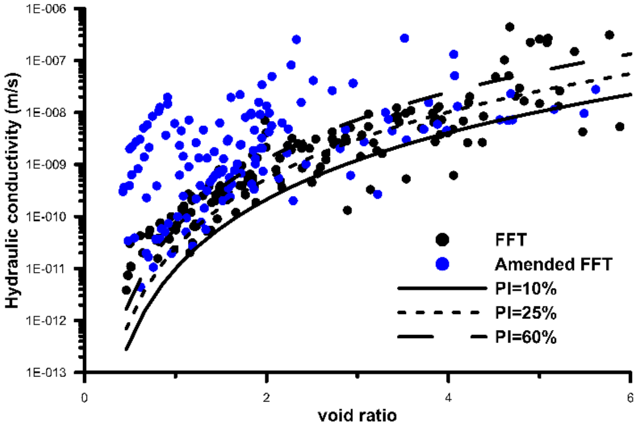

Figure 1. e-k curves for the data sets

Figure 1 shows the complete data set of k-e measurements, plotted as FFT or amended FFT. Also plotted on Figure 1 is prediction one of the modified methods presented by Babaoglu and Simms (2017), the form of the equation originally suggested by Samarasinghe et al (2002):

$$k = 2\times10^{-12}\left(PI\right)\left[\frac{e^{5}}{1+e}\right] \tag{1}$$

Equation 1 is presented for PI values of 10, 25, and 60, where 25 is the average PI of all the data. The equation is optimized for FFT – a good fit for amended FFT could be obtained if the multiplier value was increased, but this would result in a poor prediction for FFT. Atterberg limits alone cannot be used to explain the range of hydraulic conductivity results. Some of the amended FFT samples contain high amounts of sand whereas some of the data sets didn't contain at all.

However, many of the FFT and amended FFT data sets exhibit similar shapes. Figure 2 shows the same data as Figure 1 normalized with the measured hydraulic conductivity at a void ratio of 2.5, This observation suggests there is some utility to using a single measurement at high void ratio, which could be relatively quickly obtained, to improve the performance of predictive equations such as Equation 1.

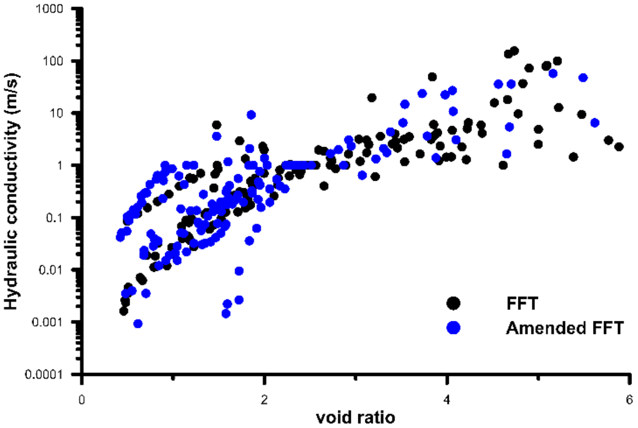

Figure 2. Hydraulic conductivity normalized with value at e=2.5 for each data set.

Previous research suggested that using predictors that contain information on the tailings at void ratio higher than the LL might improve performance, as oil sands tailings are typically deposited well above their liquid limit. The compressibility curve itself is one such potential predictor. The hydraulic conductivity and compressibility of all FFT samples are shown in Figure 3. There are obviously strong similarities between the shape of the compressibility curves and k-e relationship.

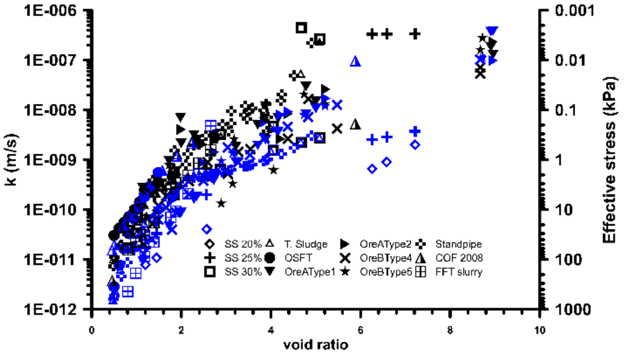

Figure 3. The relationship between hydraulic conductivity – void ratio - effective stress for untreated FFT samples

3 PREDICTING K-E FUNCTION USING THE COMPRESSIBILITY FUNCTION

For many datasets, a relationship between log e and log k at a given effective stress can be determined. For example, it was found that the following equation provides a strong fit to many of the data sets:

$$\log k = \frac{\log e}{A} - B \tag{2}$$

Figure 4 shows three examples of fits to this equation, where A= 0.2 and B=10.5, k_{sat} has units of m/s. Figure 4c shows a poor fit, this data set is from a sample with a relatively high concentration of sand (46%). However, this for this data set and for a few others, the fit could be improved by changing the offset.

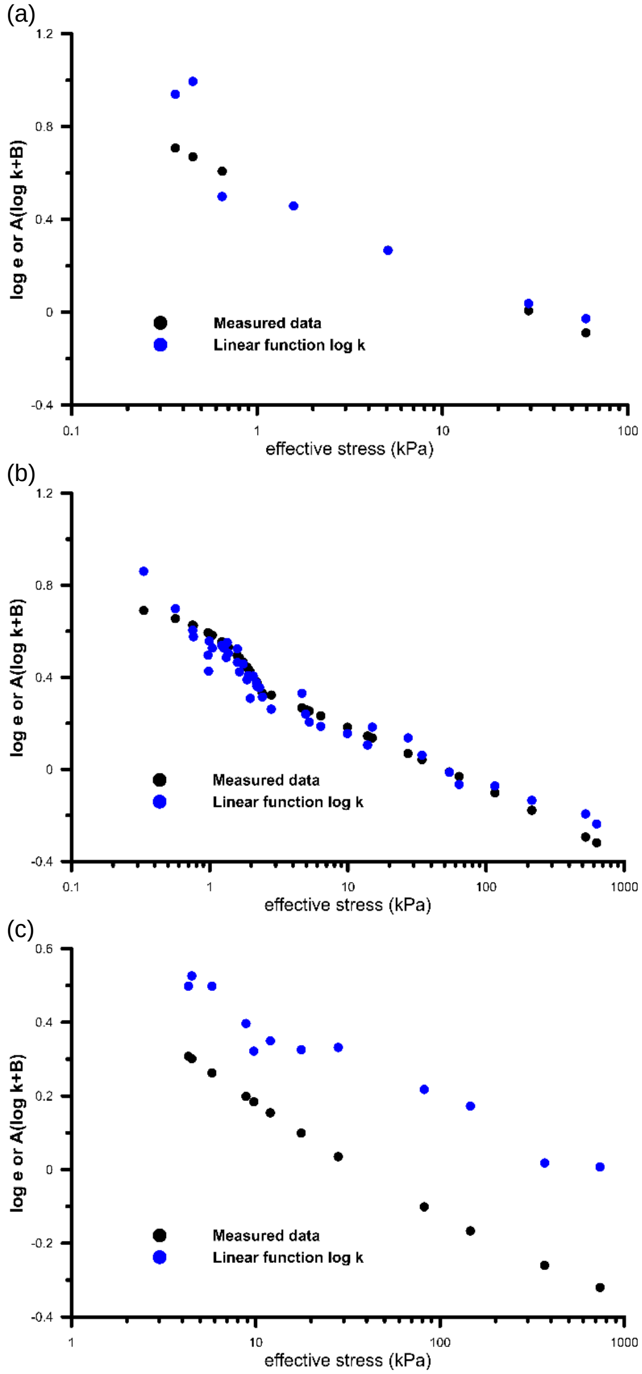

Figure 4. Three comparisons of correlations between compressibility and k-e functions, for individual data sets

Each predictive method is compared in Figure 5 where the cumulative fraction of all absolute errors, for all 400 measurements and predictions, is plotted in terms of cumulative fraction versus log absolute error. A log absolute error of 1 means that all errors in the given fraction are below an order of magnitude. Notably, the predictions using the compressibility correlation (Equation 2), slightly underperform the Atterberg limit based predictive method (Equation 1). Equation 2 gives 83% of all error below an order of magnitude, whereas Equation 1 gives 75% of all errors below an order of magnitude. This was somewhat unexpected, as it was assumed that the compressibility function gives more information of the tailings at the higher void ratios, and therefore would potentially be a better predictor than the Atterberg limits.

By scaling both Equation 1 and Equation 2 to the measured void ratio at ~ 2.5, a substantial improvement in the predictions was observed for both methods. The best performance remained was with the scaled Equation, which gives 96% of all errors less than 1 order of magnitude, compared to 94.5% for scaled Equation 2.

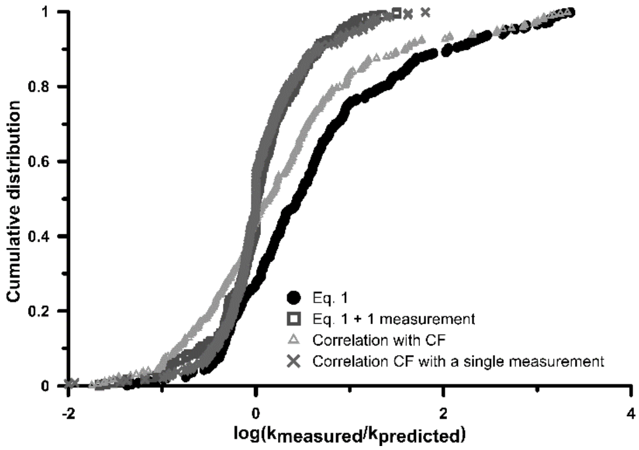

Figure 5. Cumulative distribution errors for all methods – a log absolute error of 1 equals 1 order of magnitude

However, often for individual data sets, the scaled compressibility equation gave a very good fit. Figure 6 shows a very good fit provided by the scaled Equation 2. It bears investigation into the characteristics of the individual data sets to see why one method outperformed the other.

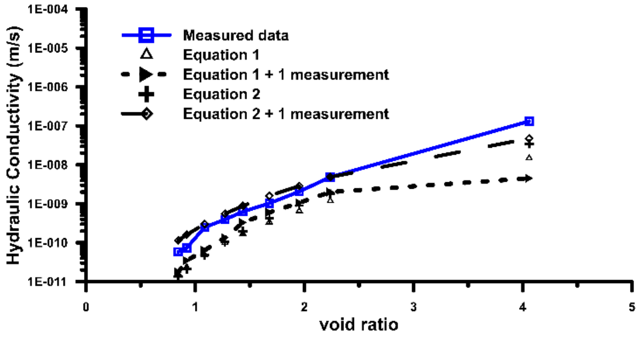

Figure 6. Comparison of predictive methods for East pond ILTT data set

4 DISCUSSION

The improvement of the predictive equation using a single measured value is not surprising. Measurement of a single hydraulic conductivity value at the high range of void ratio, can be done relatively quickly (less than a week) for a conventional slurry consolidometer test, or perhaps even more rapidly using a sedimentation column, where deformation is strongly controlled by the void ratio at the tailings–water interface and the pore-water pressure gradient remains close to the initial gradient of total stress at the start o the test – indeed under these conditions determination of the hydraulic conductivity can be straightforward as shown by Pane and Schiffman (1997). Compressibility curves can be inferred from point measurements of pore-water pressure and density.

Figure 7 shows an example of the relative accuracy of k-e functions predicted by the proposed predictive equations. Three k-e functions are used, which have the same hydraulic conductivity at an initial void ratio of 4, but an order of magnitude difference at a void ratio of 1. Specifically, the functions are 1.75 x 10^{-9} m/s x $e^{6.33}$, 1.75 x 10^{-10} m/s x e^{8}, and 1.75 x 10^{-11} m/s x $e^{9.66}$, for the high k_{sat}, the base case, and the low k_{sat} functions. The initial depth of the deposit is 10 m and the compressibility curve is such that the final height is 4.2 m, which is equivalent to an average void ratio of 1.1 and a solids content of 66%. While the demand on the required accuracy differs from project to project, it is probable this level of accuracy is sufficient to use these equations as screening tools for proposed tailings technology amendments.

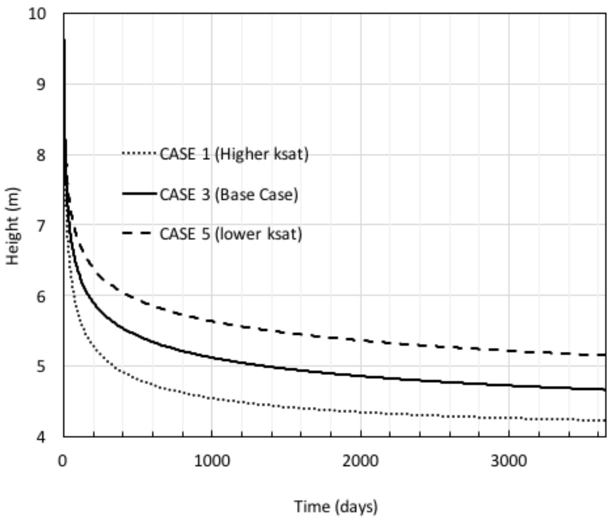

Figure 7: Sensitivity of prediction of consolidation of 10 m deposit where k_{sat} varies by two orders of magnitude at a void ratio of 1.

5 CONCLUSION

The performance of tailings management plan is highly dependent of the consolidation behaviour of fluid fine tailings. The relationship between effective stress-void ratio and hydraulic conductivity dominates this behaviour; however, it can be difficult or expensive to assess these parameters, especially for permeability. This paper has discussed two types of method to predict the hydraulic conductivity function, one based on Atterberg limits, the other from the compressibility function itself. When optimized using a data of 20 measured k-e function from oil sands tailings, it was found that both methods could be much improved by using a measured hydraulic conductivity value at low stress or high void ratio. The accuracy was such that > 90% of 400 hydraulic conductivity measurements were predicted within an order of magnitude. Therefore, these equations appear to have value at the very least as screening tools for rapid evaluation of changes to tailings technology on the consolidation behaviour.

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