Rapid Estimation of Hydraulic Conductivity for Fluid Fine Tailings

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k-e is essential for calculating settlement rates & strength of oil sands tailings

Determination of highly variable consolidation properties of FFT can be time consuming and/or expensive

Rapid estimation/measurement of k will accelerate innovation in the industry → quick evaluation to new technologies
Three methods are developed to estimate k-e relationship

Method 1:
- Estimate k-e relationship using Atterberg limits / compressibility curves with a single measured data point at a higher void ratio

Method 2:
- Calculates k from 1D profiles from the variations in pore water pressures and water content

Method 3:
- Robust estimations of k-e function using settlement curve & compressibility curve at the final condition
Method 1: Using CC or Atterberg Limits

- There are number of predictive models available in the literature → not accurate to estimate at higher void ratios

\[ k = 2 \times 10^{-12} (PI) \left[ \frac{e^5}{1 + e} \right] \]

- The performance of the predicted model can be improved by using a single measured data point
- Total of 28 data sets were evaluated: 13 FFT & 15 amended FFT

- FFT is deposited at higher e → a measured k at that range improves the performance

- Compressibility curve is evaluated as a predictor → shape of k-e and σ’-e is similar
Method 1: Using CC or Atterberg Limits

- Linear relationship provided acceptable estimations for most of the data sets

- The offset can be improved by using a single measured $k$ value at high void ratio

- Parameters A & B are soil specific → estimated at higher $k$-$e$

- 96% of predicted $k$ are within an order of magnitude
Method 1: Using CC or Atterberg Limits

- Using optimized $A = 10.3$ & $B = 0.2$
  → percentage error decrease to 81%

- Linear relationship can be rearranged & corrected using a measured $k$ value at $e_0$:

$$\log k = \frac{\log e}{A} - B \quad \rightarrow \quad k = k_{\text{measured at } e_0} \left( \frac{e^5}{e_0^5} \right)$$

$$k = 2 \times 10^{-12} (PI) \left[ \frac{e^5}{1 + e} \right] \rightarrow k = k_{\text{measured at } e_0} \left( \frac{e^5}{e_0^5} \right) \left( \frac{1 + e_0}{1 + e} \right)$$
Method 1: Using CC or Atterberg Limits

- **k** at e0 could be calculated using the method of Pane and Schiffman:
  \[
  k = \frac{(1 + e)v_s}{G_s - 1}
  \]

- But for some in-line flocculated material, flocculation and properties of the tailings can change substantially over the first 24 hours post-deposition.

- Therefore, using a **k** value measured at a lower void ratio (say post-sedimentation, or first load increment in an LSC test) would be more appropriate.
Method 2: Instantaneous Profiling Method

- Originally proposed by Watson (1966)
- Determines $k$ for unsaturated porous materials
- Based on Darcy’s law
- $k \rightarrow$ monitoring changes in $w$ and total potential

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial \phi}{\partial z} \right) \rightarrow \frac{\partial w}{\partial t} = K \left( \frac{\partial^2 \phi}{\partial z^2} \right)$$

- Advantage:
  - $k$ is independent of any dewatering mechanisms
  - Direct measurement technique

- Disadvantage:
  - Requires high-resolution measurement profiles
Method 3: Robust back-calculation of k from settlement curves

- Calculates k-e relationship from settlement curves
  - Compressibility function can be determined from density profiles & final PWP measurements
  - Initially assuming a power-law k-e function: \( k = M e^P \)

- The analysis is completed using Sed-LSC using UNSATCON

- Initially, parameters M and P are assumed → LSC analysis were conducted → repeat the process with different M and P

- 2 pairs of M and P will provide 2 settlement curves:
  - Need to use measured settlement curve
  - Scale the predicted settlement curves to the measured data points
Method 3: Robust back-calculation of \( k \) from settlement curves

- By varying \( M \) and \( P \), settlement curves are constructed and scaled to measured data points:
  \[ k = Me^P \] \( \rightarrow \) \( M_1 t_1 = M_2 t_2 = M_N t_N \)

- Intersection of the lines will give the optimal \( M \) and \( P \)

- Method works with even 2 constructed lines
CS2 Column test

- Sun et al. (2014)
- Large strain consolidation of thickened oil sands tailings were evaluated
- Pore-water pressure & effective stress & solids content readings are provided
- Initial height = 2.5 m
- Uses gamma traversing densitometry for solids concentration
Specific gravity & compressibility equation is calculated from the final condition → $G_s = 2.6$

Δ$h$ is assumed to be linear until Day 11

**Method 1:**

- $e_0$ is 2.65
- $K_{measured \ at \ e_0} = 1.24 \times 10^{-6} \text{ m/s}$
- Using Pane & Schiffman (1997)'s method to calculate initial $k$ → assuming zero effective stress

\[
k = k_{measured \ at \ e_0} \left( \frac{e^5}{e_0^5} \right) \quad \text{&} \quad k = k_{measured \ at \ e_0} \left( \frac{e^5}{e_0^5} \right) \left( \frac{1 + e_0}{1 + e} \right)
\]
Method 2:
- For IPM: Day 88 is selected to evaluate
- $\Delta z = 0.1$ m
- $K-e$ is estimated by averaging the known profiles of $e$ a days 60&125
Method 3:

- Settlement & Compressibility curves are required
- Data is extracted at Day 347 → to obtain the compressibility curve
- 2 Sed-LSC analysis are conducted using M (10^{-10}, 10^{-8}) and P (8,4) combinations
  - Curves are shifted to measured settlement points at Days 11 & 125 → \( M = 10^{-8} \) & \( P = 4.85 \)

Data from Sun et al. (2017)

Best fit curve
- Method 1&3 provided a better performance compared to IPM
- Method 1 & 3 requires settlement curve data
- Theoretically, IPM should provide the best performance → “data-hungry” method requiring high-resolution measurement profiles
- For more accurate application of the method, a detailed profile of density/water content measurements is needed
Discussion

- LSC analysis is conducted to calculate PWP and void ratio using k-e function from Method 3
- PWP estimations disagreed with the measured data → due to shift in compressibility function over time
- Evolving compressibility function can be tracked using the paired measurement of density & PWP → 1 measurement of PWP is needed (higher optimal k-e relationship)
- Evolving CC may substantially impact the settlement rate and final H of deep deposits
Capacitance based sensors are used and tested for various fine soils including centrifuged FFT → measured soil dielectric constant

SANTEK Sensors:

**Advantages:** Continuous measurements, No contact with the soil, Sensitive to small changes, Repeatability

**Disadvantages:** Needs a calibration equation, Zone of influence is small, Sensitivity to air gaps surrounding the sensor can alter the readings, Reading location must be the same

Automation of the sensors
Automation of EnviroScan Sensors

![Image of sensors setup]

- ○ z=11.7 cm
- ▲ z=17.7 cm
- ▽ z=13.7 cm
- × z=19.7 cm
- □ z=15.7 cm

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<th>Solids content (%)</th>
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<td>34.4</td>
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<tr>
<td>34</td>
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<tr>
<td>33.6</td>
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<th>time (hours)</th>
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<td>150</td>
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<td>200</td>
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Acknowledgements


Miller, W. G. 2010. Comparison of geoenvironmental properties of caustic and noncaustic oil sand fine tailings, University of Alberta.


