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PROTOTYPE COLUMN TEST TO ESTIMATE HYDRAULIC CONDUCTIVITY OF SLURRY TAILINGS

Yagmur Babaoglu, Paul H. Simms
Department of Civil & Environmental Engineering, Ottawa, Ontario, Canada

ABSTRACT

Large strain consolidation behaviour of mineral slurries regulates the performance of tailings management and reclamation plans. Hydraulic conductivity-void ratio relationship especially influences this behaviour, dominating the long-term performance of fine-grained slurries with higher initial water contents. However, the determination of this function can be very challenging and time-consuming, considering the long duration of the consolidations test and large variation in hydraulic conductivity with the void ratio. A laboratory test column study was conducted to evaluate the consolidation behaviour of thickened gold tailings. The test column was instrumented with tensiometers and Enviroscan (capacitance-based) sensors to determine the pore water pressures and volumetric water changes, respectively. Also, a robotic arm is connected to the sensor probe for more detailed profiling. The collected data is then utilized to estimate the hydraulic conductivity of the tested materials using the Instantaneous Profiling Method (IPM). Finally, the measured data and the predicted behaviour of the material are compared using a large strain consolidation software.

RÉSUMÉ

Le comportement de consolidation à grande contrainte des boues minérales régule le rendement des plans de gestion et de remise en état des résidus. La relation entre la conductivité hydraulique et le rapport des vides influence particulièrement ce comportement, dominant les performances à long terme des suspensions à grains fins avec une teneur en eau initiale plus élevée. Cependant, la détermination de cette fonction peut être très difficile et longue, compte tenu des longues durées des tests de consolidation et des grandes variations de conductivité hydraulique avec rapport de vide. Une étude en colonne d'essai en laboratoire a été menée pour évaluer le comportement de consolidation des résidus d'or épaissis. La colonne d'essai a été instrumentée avec des tensiomètres et des capteurs Enviroscan (basés sur la capacité) pour déterminer respectivement les pressions interstitielles et les changements volumétriques de l'eau. En outre, un bras robotique a été connecté aux capteurs pour un profilage plus détaillé. Les données collectées sont ensuite utilisées pour estimer la conductivité hydraulique des matériaux testés en utilisant la méthode de profilage instantané (IPM). Enfin, les données mesurées et le comportement prévu du matériau sont comparés à l'aide d'un logiciel de consolidation à grande déformation.

1 INTRODUCTION

Large amounts of water are used for mineral processing in many types of mining operations. Water acts as a lubricant for the grinding process, facilitates extraction and separation of the ore particles, as well as assists hydraulic transportation of tailings to the deposition sites. Large amounts of water are added to the by-product of these operations; usually, 100% for hard rock mining, 200% for bauxite and oil sands tailings), resulting in the production of large volumes of mineral wastes to be deposited in tailings dams (Simms 2017; Vick 1990; Wills and Napier–Munn 2006).

The initial loose state of these high-water content materials will densify as the soil drains and consolidates over time. However, prior to deposition, understanding the consolidation behaviour of these materials is essential. It is well-known that the geotechnical behaviour of soft soils is very dependent on the compressibility and hydraulic conductivity functions, which can be highly variable for fine-grained soils. Determination of this variable parameter can be very time consuming or expensive to obtain from conventional laboratory tests. Therefore, rapid estimation of the *k-e* curve is desirable, as it will accelerate innovation in the industry by allowing quick evaluation of new or improved technologies in terms of their long-term dewatering potential.

Compared to compressibility, the determination of the hydraulic conductivity of this fine material is more complex. Determining hydraulic conductivity at a range of void ratios using conventional methods, such as the large strain consolidation test, can take a considerable amount of time for tailings and other soft soils, often months or even up to a year (Pane et al. 1983; Suthaker and Scott 1996; Znidarčić et al. 1986). Furthermore, the behaviour of soft soils, slurry or tailings, at a low void ratio is complex, which poses difficulties for the determination of the hydraulic conductivity-void ratio relationship of these materials.

This study focuses on calculating the *k-e* relationship using the Instantaneous Profiling Method (IPM) (Watson 1966), which derives from Darcy's equation, from a column or 1-D sedimentation test using 1D profiles of pore water pressure and water content. Similar researches have been conducted using the IPM method such as Leung et al. (2016), Askarinejad et al. (2012), Dikinya (2005) and Fisher et al. (2008). A particular advantage is that the computed hydraulic conductivity is independent of the compressibility curve, which may shift during consolidation at low stresses (Hawlader et al. 2008). A column setup is designed to allow for non-destructive measurements of volumetric water content profiles and an automation system to allow for detailed profiling using capacitance-based sensors. This setup will allow for rapid, simultaneous and non-destructive calculation of *k-e* curve using the IPM method. The consolidation of gold tailings are examined at different water contents. The measured settlement behaviour is then compared with the predicted behaviour using a large strain consolidation software, employing the measured *k-e* values.

2 METHODOLOGY

The *k-e* relationship is determined by using the Instantaneous Profiling Method (IPM) initially proposed by Watson (1966), but adopted for large strain conditions. The instantaneous profiles in the column can be established by the profiles of the macroscopic flow velocity, the potential gradients in water content and hydraulic head, as per the groundwater flow equation. The method allows for a simultaneous, rapid and non-destructive calculation of k values as presented in Equation 1.

$$\frac{\partial \theta}{\partial t} = K\frac{\partial^2 h}{\partial z^2} \qquad [1]$$

where θ is the volumetric water content, *t* is time, *z* is the height above the datum, and *h* is the total potential. Equation 1 is based on the flow-through constant volume of element, but in a case with changing densities (for saturated conditions), this equation will remain applicable for a constant volume of solids (Fox and Berles 1997). The volumetric water content component can be substituted by void ratio, and Equation 1 can be expressed using the central difference scheme.

$$\frac{\left(\frac{e_{t1}}{1+e_{t1}}\right)-\left(\frac{e_{t3}}{1+e_{t3}}\right)}{t_1-t_3} = k\frac{h_1+h_3-2h_2}{\Delta z^2} \qquad [2]$$

where *k* can be calculated at *k (z, t)* at any instant and location. For the validity of the equation in saturated conditions, the component z should be the height of solids instead of a constant elevation or constant change in the elevation, which can be determined from the distribution of void ratio with depth over time. If the change of solids height or *Δz* is small over the time step, then this component can be assumed constant.

For the IPM method to successfully determine the *k-e* relationship, the resolution of the volumetric water content and pore water pressure distribution should be sufficiently detailed. High-resolution density or water content readings are imperative. The pore-water pressures are usually smoother and can be adequately interpolated. The advantage of this methodology is that it is independent of any assumptions with respect to dewatering mechanisms such as sedimentation, consolidation, structuration or creep.

3 EXPERIMENTAL SETUP & TESTED MATERIALS

The application of the methodology was tested using self-weight consolidation columns on thickened gold tailings, presented in Figure 1. The height of the column is 60 cm and has ten tensiometer inlets (including one at the bottom) to measure pore water pressures. The outer column diameter is 12 inches, and a two-inch PVC pipe is located in the middle of the column to accommodate water content sensors. The middle pipe is connected to the bottom of the column using a metal connection piece and multiple O-rings to eliminate leakage.

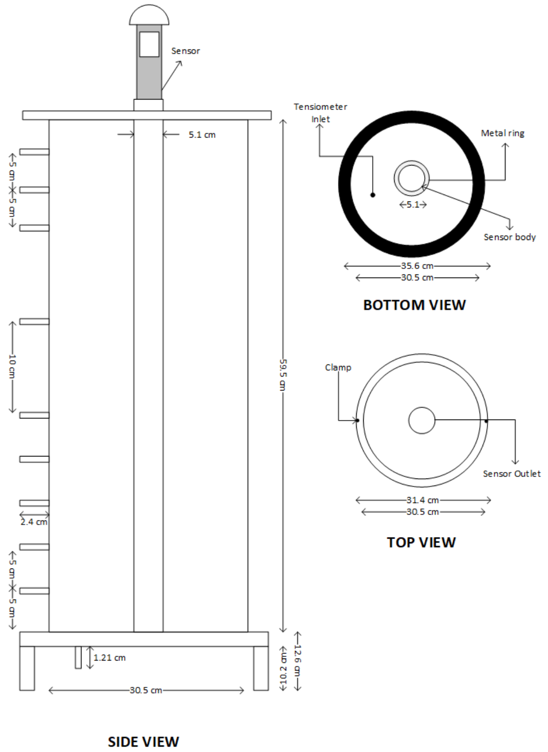


Figure 1. The schematics of the self-weight consolidation columns used in this study

The experimental setup is designed to measure high-resolution water content profiles without interfering with the consolidation behaviour of tested fine-grained soils. For this experiment, capacitance-based EnviroScan sensors are utilized to determine high-resolution volumetric water content profiles. These sensors allow for moisture content measurements every ten centimetres.

For more-detailed soil-water content profiles, the sensors would require vertical movement during testing, which can be achieved using an automation design. The probe is connected to a motor, which is then controlled by an Arduino board. Arduino is an open-source electronics platform applicable to hardware and software applications (Arduino 2015) and acts as a controller for the motor movement in this experiment. A 12V DC linear actuator is selected as the motor due to the adequately controlled retraction of its shaft. The probe has connected the shaft of the motor via metal cuffs, and the motor is controlled by the Arduino board using multiple relay modules (for back-and-forth movement of the shaft) and connectivity relays (for voltage compatibility). The application of the automation system allowed the authors to measure the moisture content at every two centimetres. The settlement is observed using two high-resolution cameras throughout the experiment.

For the initial evaluation of the self-weight consolidation behaviour of fine-grained slurried tailings, a thickened gold tailings were selected and tested at three different solids contents. The conventional gold tailings usually have solids content around 50% (GWC=100%), whereas this value can increase up to 70% or higher with the thickening technologies. This specific gold tailings shipped to Carleton University at a gravimetric water content of 47.5%, similar to Test #3 (Thomas 2015). Tailings below a certain density are subjected to grain size segregation, all the densities tested in this paper are above that threshold.

Table 1 summarized the initial and final conditions of all three tests performed in the self-weight consolidation column. The gradation of the gold tailings is presented in Figure 2, and for more details on the geotechnical properties of the material, please refer to Thomas (2015). Only three tensiometers are utilized (only four inlets are available for the thickness of the materials in the column), and the pore water pressure readings in-between locations are estimated using non-linear regression models in MATLAB. The volumetric water content profiles are measured with 2 cm intervals. The tests are performed for 24 hours, but the settlement of solid particles completed prior to that. The tailings settle very quickly, and in order to avoid any settlement at the beginning, the columns are filled in a single batch.

Table 1. Initial and final conditions of thickened gold tailings tested in the laboratory.

	Test #1	**Test #2**	**Test #3**
Initial θ (%)	53	64	61
Initial *w* (%)	35	55	48
Solids content (%)	74	64.3	67.5
Initial void ratio	1.12	1.77	1.54
Initial height (cm)	26.2	33.8	28.0
Final height (cm)	23.4	25	22.3
Tensiometer positions (in cm, from the bottom)	5-15-20	5-15-25	5-15-20
Test duration	24 hours	24 hours	24 hours
Settlement duration	11.8 hours	6.6 hours	8 hours

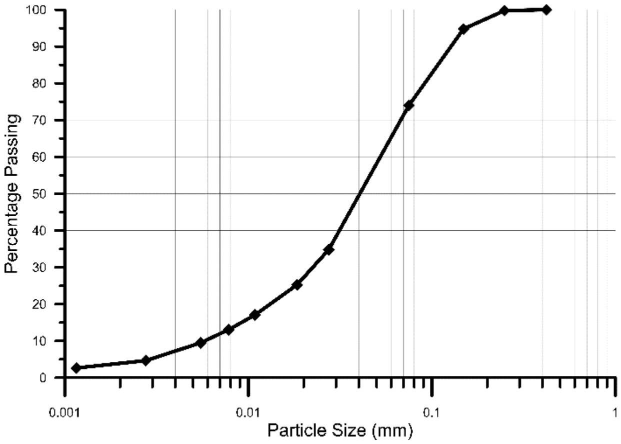


Figure 2: The gradation of gold tailings utilized in the experiments

Total potential measurements are calculated by adding the measured pore water pressure measurements and gravitational head. They are presented in Figure 3 at different heights and times for all experiments.

The volumetric water content profiles of the three tests are presented in Figure 4. During testing, a restrained of EnviroSCAN sensors is discovered. Each sensor averages the reading within a 10 cm depth, and closer to mudline, a sudden increase in the readings is detected. This is due to the sensor reading partially from water, hence the average value increases. For an accurate implementation of IPM, the sensor should not be influenced by the water readings. Therefore, only the measurements within the soil are considered in this study.

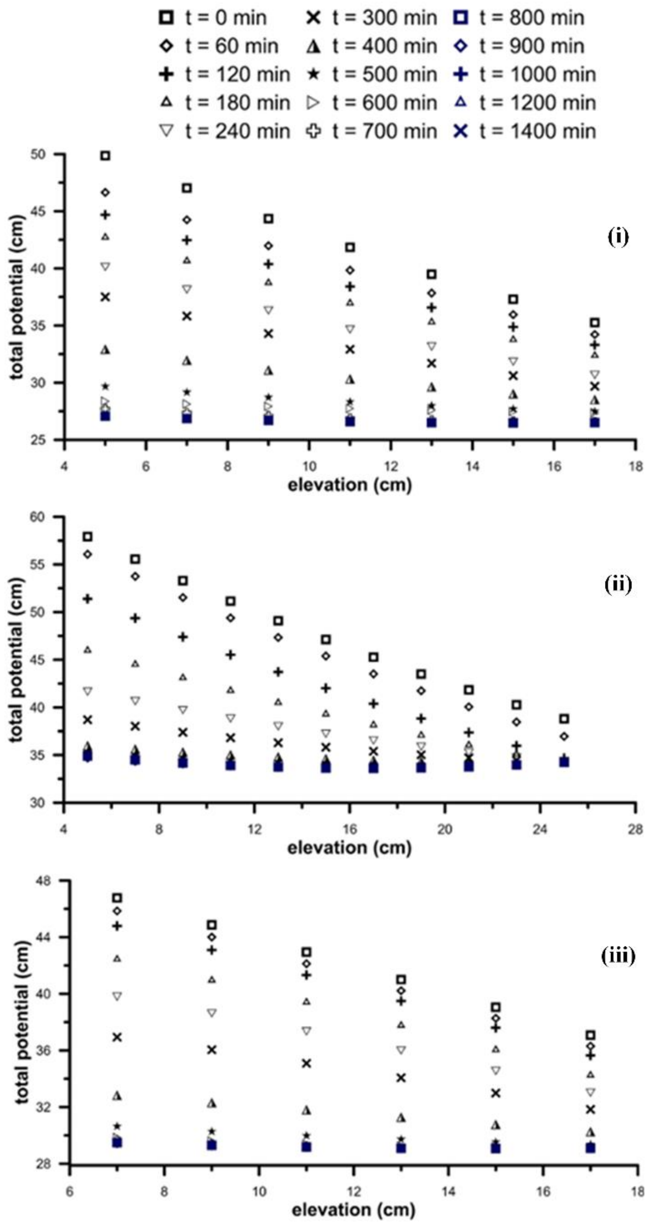


Figure 3. Total potential profiles for (i) Test #1, (ii) Test #2 and (iii) Test #3

4 RESULTS AND DISCUSSION

The final water content profiles and the settlement of the tailings for all three tests are presented in Figure 5. EnviroSCAN sensors require calibration prior to utilized in the experiment. One of the things the authors learned is that each sensor would require calibration, and it should be calibrated at each depth (even for the same sensor). The calibration was completed using the initial water content and the final volumetric water contents presented in Figure 5.

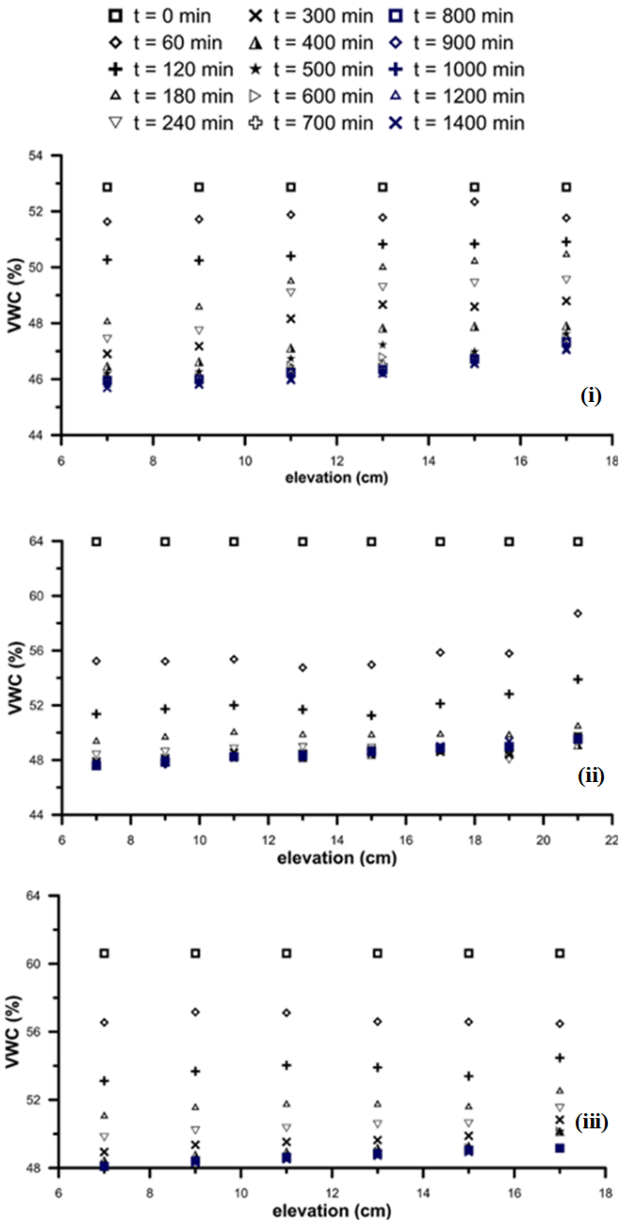


Figure 4. Volumetric water content profiles for (i) Test #1, (ii) Test #2 and (iii) Test #3.

The hydraulic conductivity can be determined by solving Equation 2, which is presented below for all three cases. Figure 6 demonstrates the *k-e* data points calculated at different heights.

Test #1: $$k(m/s) = 8.7 \times 10^{-7} e^{4.0} \qquad [3.1]$$

Test #2: $$k(m/s) = 2.1 \times 10^{-6} e^{5.5} \qquad [3.2]$$

Test #3: $$k(m/s) = 1.45 \times 10^{-6} e^{6.5} \qquad [3.3]$$

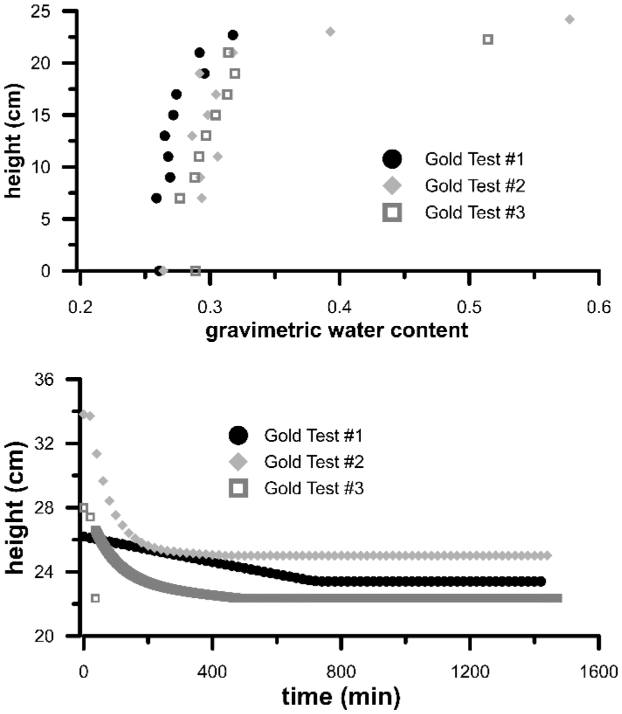
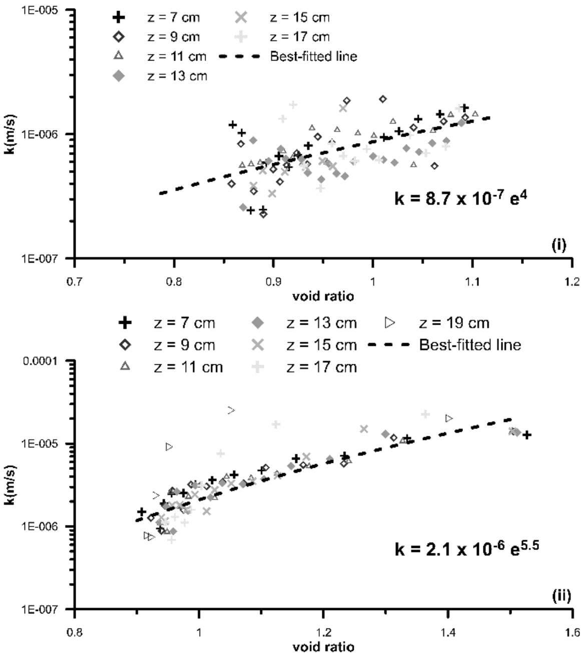


Figure 5. The final conditions of the three tests



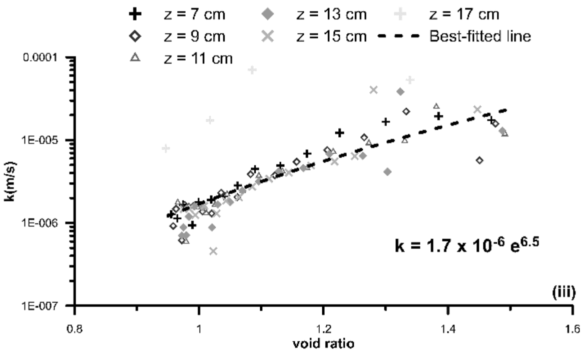


Figure 6. *k-e* relationships for (i) Test #1, (ii) Test #2 and (iii) Test 3

To demonstrate the accuracy of the calculated *k-e* relationships, the authors employed the large strain consolidation analysis model UNSATCON (Qi et al. 2017a; Qi et al. 2017b) to compare the final measured and the modelled settlement profiles. The model utilizes a mass-conservative formulation and piecewise linear framework to determine the large-strain consolidation behaviour of both unsaturated and saturated soils. The conducted experiments in this study are in a fully saturated condition.

The structure of Equation 2 allows for the calculation of *k* values at different times and locations during the experiments, which may lead to dispersed *k-e* data. The best-fitted power equation is selected to represent each test, as presented in Figure 6, using non-linear regression models in MATLAB. To ascertain the representation of the determined permeability equations for each test; the experiments are simulated using UNSATCON, and the measured volumetric water content profiles are compared with the predicted data from the model at different times and locations. The predicted volumetric water content profiles provided a very good agreement with the measured profiles (measured using EnviroSCAN sensors) for all three tests.

Two separate compressibility curves can be determined using the experimental setup: the first one can be calculated using the measured pore water pressures and volumetric water contents throughout the experiment, and the second one can be determined from the final condition. The final effective stress-void ratio relationship is determined from the final condition (presented in Figure 7), and the equations are calculated as:

Test #1: $e = 0.91\sigma^{-0.12}$ [4.1]

Test #2: $e = 1.02\sigma^{-0.11}$ [4.2]

Test #3: $e = 0.93\sigma^{-0.07}$ [4.3]

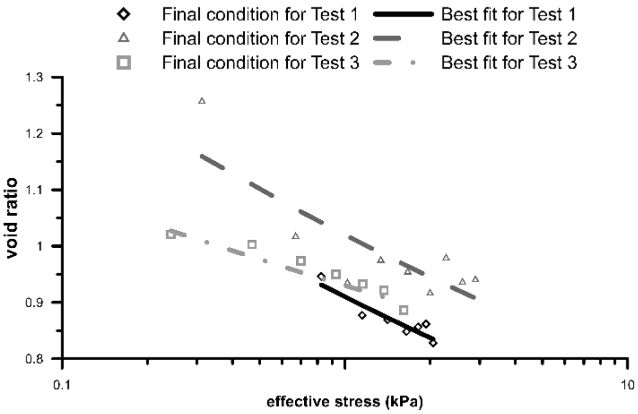


Figure 7. The compressibility curves determined from the final condition

It should be noted that Test #2 has the highest initial water content, and the final compressibility curve, as presented in Figure 7, differs from the other two experiments. If the compressibility equation is calculated using the measured pore water pressures and volumetric water contents during the experiment, the parameters change to:

Test #1: $e = 0.92\sigma^{-0.11}$ [5.1]

Test #2: $e = 0.99\sigma^{-0.13}$ [5.2]

Test #3: $e = 0.99\sigma^{-0.16}$ [5.3]

The settlement behaviours of thickened tailings are modelled and shown in Figure 8 using the effective stress-void ratio-hydraulic conductivity relationships presented in Eqs. 4. The initial settlement behaviour for Test #1 did not agree with the modelled behaviour which can be attributed to a malfunction in the camera system at the beginning of the tests; hence the settlement was estimated for the first ten hours (that issue was fixed for the other two experiments); however, the model provided good agreement with the final measured height. Whereas for Tests 2 and 3, UNSATCON underestimated the final settlement height, which is dependent on the compressibility equations provided in Equations 4.2 and 4.3. The final settlement heights agree better with the predicted values if Eqs.5 is utilized in the model, as displayed in Figure 9.

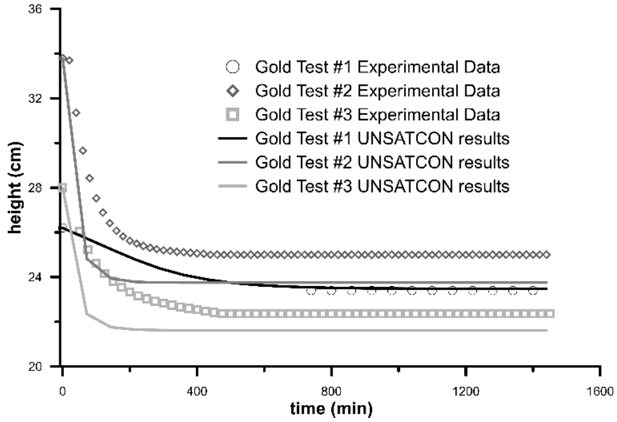


Figure 8. Settlement behaviour of thickened gold tailings at different volumetric water contents (Test #1: 53%, Test #2: 64% and Test #3: 61%) using Equation 4.

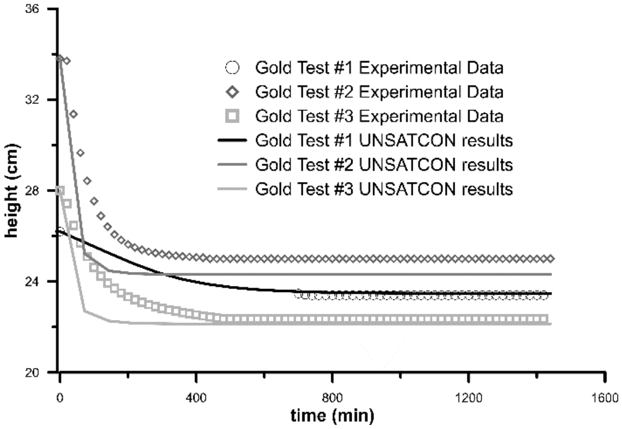


Figure 9. Settlement behaviour of thickened gold tailings at different volumetric water contents (Test #1: 53%, Test #2: 64% and Test #3: 61%) using Equation 5.

As mentioned previously, predicted water content profiles are compared with the measured data (at different heights using UNSATCON) to analyze the capability of the *k-e* relationships provided in Eqs.3. The measured values agreed well with the predicted data for all three tests. Figure 10 presents the comparison for Test #2.

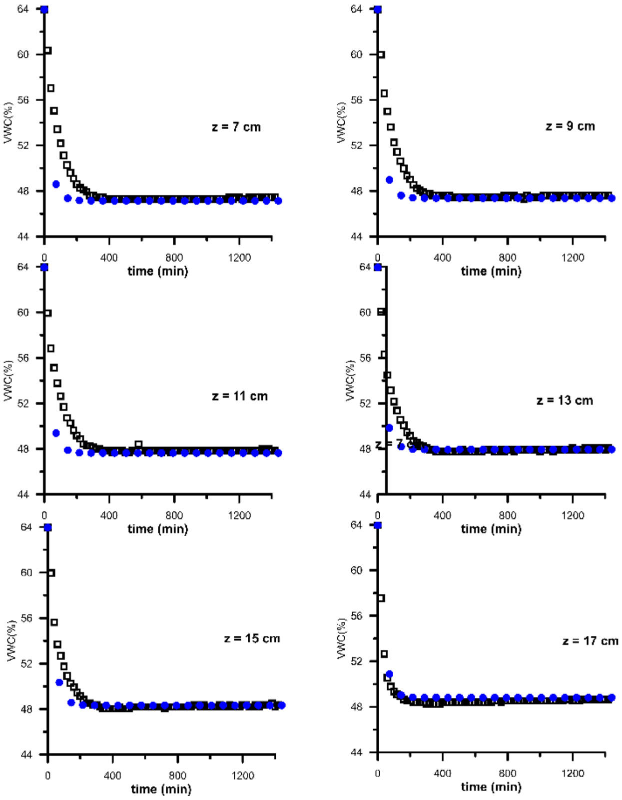


Figure 10: Comparison of predicted and measured volumetric water content profiles at different depths for Test #2.

5 SUMMARY AND CONCLUSIONS

This paper examined the application of the IPM method, which derives from Darcy's law, to calculate the *k-e* relationship for fine-grained thickened gold tailings. The hydraulic conductivity curve can be determined by the variations in pore water pressure and volumetric water content profiles from a 1D column test. Capacitance-based EnviroSCAN sensors are selected for this application to provide sufficient resolutions of water contents with depth, and an automation system is implemented to provide vertical movement to the probe, achieving high-resolution measurement profiles.

The settlement behaviours, along with the changes in the volumetric water content profiles, are compared with the estimated curves predicted by a large strain consolidation analysis program UNSATCON, using the calculated *k-e* curves from the IPM method. The results demonstrated small discrepancies between the measured and predicted settlement behaviour for Tests 2 and 3 (which can be attributed to the selected compressibility equation as they provide a better fit if Eqs.5 is used in the model). However, the predicted volumetric water content profiles at different heights and durations agreed well with the measured data, which demonstrated the potency of the calculated *k-e* curves from the IPM model.

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