Tracking changes in hydraulic conductivity of soil reclamation covers with the use of air permeability measurements



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ABSTRACT

Soil covers are used extensively in the reclamation of lands disturbed due to industrial activity such as mining. The hydraulic conductivity of these covers changes over time as the result of weathering and bioperturbation processes. The Guelph permeameter was used at Syncrude's oilsands mine to track the soil structure evolution, as represented by changes in hydraulic conductivity. Although this method was successful, it is also time consuming. A rapid alternate method of tracking hydraulic conductivity changes is proposed in which changes in air permeability rather than hydraulic conductivity are measured. A prototype air permeameter was constructed and field and laboratory trials were conducted. The results from these trials are presented in this paper.

RÉSUMÉ

Les barrières de recouvrement sont abondamment utilisées dans la récupération de terrains perturbés par les activités industrielles telle que l'exploitation minière. La conductivité hydraulique de ces barrières change au fil du temps en raison des processus d'érosion et de perturbations biologiques. Le perméamètre Guelph a été utilisé à la mine de sables pétrolifères de Syncrude pour suivre l'évolution de la structure du sol, telle que représentée par les changements de la conductivité hydraulique. Bien que cette méthode soit réussie, elle nécessite beaucoup de temps. Une méthode alternative rapide pour suivre les changements de conductivité hydrauliques est proposée. Dans cette nouvelle méthode c'est les changements dans la perméabilité à l'air plutôt que dans la conductivité hydraulique qui sont mesurés. Un prototype de perméamètre à air a été construit et des essais de terrain et de laboratoire ont été accomplis. Les résultats de ces essais sont présentés dans cet article.

1 INTRODUCTION

The properties of soil covers will evolve following placement as a result of changes in secondary structure. These changes are brought about by physical or biologic processes such as freeze-thaw or wet-dry cycling, settlement of the waste material below the cover, and vegetation rooting. These processes act to produce macropores and fractures which alter the hydraulic conductivity and the transport rates of both water and salt.

One method of tracking these changes is by taking repeated measurements of field saturated hydraulic conductivity. Meiers et. al (2006) report on the measurement of hydraulic conductivity of soil covers on overburden waste over a five year monitoring program at the Syncrude Canada Ltd. oilsands mine in northern Alberta, Canada. The hydraulic conductivity was measured using a Guelph permeameter, which is a constant head well permeameter technique.

The main study area of interest was three prototype soil covers on the SW30 Dump. Figure 1 shows that the hydraulic conductivity of these covers increased significantly during the first three to four years, and appears to have reached a steady state (Barbour 2005).

Tracking changes in hydraulic conductivity with this method has been successful but also extremely time consuming. Due to the fine-grained nature of cover materials, the soil is prone to smearing during well bore installation. This effect in combination with the relatively low hydraulic conductivity often results in test durations of more than one hour and possibly underestimated values of hydraulic conductivity.

The portable air permeameter has been proposed as a rapid, inexpensive alternative to the Guelph permeameter for tracking changes in hydraulic conductivity. The method is based on the measurement of air permeability rather than saturated hydraulic conductivity.

In an unsaturated condition, the air permeability of these soils is controlled by the same secondary structure (and larger pore sizes) that control the field saturated hydraulic conductivity. Since the pores of interest are empty throughout the summer in response to evapotranspiration, measurements can be made more rapidly without having to saturate the secondary structure with water. Theoretically, the permeability of soil to air and water should be equal at identical fluid phase contents.

A field scale prototype air permeameter was constructed, and field trials were conducted at Syncrude Canada Ltd. and Suncor Energy Inc. in August 2006. Guelph permeameter measurements were taken alongside each test location so that comparisons could be made between the two methods. Supporting laboratory tests were also carried out to investigate the capabilities of the air permeameter to produce values of permeability equivalent to a conventional constant head (water) permeability test under ideal conditions.



Figure 1. GP measurements for the Syncrude SW30 Dump D3 cover (Meiers et al. 2006). Cover placement occurred during the winter of 1998-1999.

2 BACKGROUND

2.1 Guelph Permeameter Measurements

The GP method consists of a mariotte type bottle resting on the bottom of a well bore that has been augered in the unsaturated zone (Elrick and Reynolds 1992), as shown in Figure 2. A constant depth of water is maintained, so that the steady-state liquid recharge rate (Q) can be determined for calculation of the "field-saturated" hydraulic conductivity (K_{fs}) (Reynolds and Elrick 1986).

The term "field-saturated" refers to the fact that air may be entrapped by the infiltrating water, causing the measured hydraulic conductivity to be lower than truly saturated hydraulic conductivity K_s (Constantz et al. 1988).

Effects of air entrapment may be insignificant when measuring K_s on sandy soils, but not necessarily when measuring K_s on clay soils when the flow may be governed by macropores. In various studies, K_{fs} measurements in well-structured clay soils have occurred in the expected K_{fs} range for structureless sands (1 x 10⁻⁶ m/s to 1 x 10⁻⁴ m/s) instead of the K_{fs} range expected for structureless clay soils (1 x 10⁻⁹ m/s to 1 x 10⁻⁷ m/s) (Reynolds and Zebchuk 1996).

Other factors which may cause the value of K_{ts} measured with the Guelph permeameter to be underestimated for clay-rich soils with macropores include:

- smearing, remolding, and/or compaction of the well surfaces during augering, and
- small scale soil heterogeneity (Elrick and Reynolds 1992).



Figure 2. GP borehole, saturated bulb and wetting front, where: ψ is the soil water pressure head, h is the constant ponded height of water, and r is the well bore radius (from Giakoumakis and Tsakiris 1999).

2.2 Macropore Theory

Macropores are defined as pores that are significantly larger than those resulting from simple packing of elementary soil particles. The size of macropores is not as important as their continuity through the soil horizon, which allows for fluid transport (Bouma 1982). Bouma and Wosten (1979) stated that water-conducting macropores usually occupy <1% of the total soil volume.

In the dry summer months, soil is typically at water contents less than field capacity, which occurs at matric water potentials of -5 to -10 kPa (lversen et al. 2001). According to capillary theory, pores of diameter 60 to 30 μ m should be fully drained and available for air flow in this pressure range. Poiseuille's law states the flow rate depends on the fourth power of the effective pore radius for fluid filled pores (Hillel 1998). Therefore, if a soil is at field capacity, the pores contributing to air flow are governing the overall flow rate through the soil horizon.

2.3 Air Flow in Soil

As mentioned previously, the permeability (k [m²]) of soil to water and air should be equal at identical fluid phase contents. The permeability of soil is related to hydraulic conductivity using properties of the test fluid according to Equation 1:

$$k = \mu K / \rho g$$
[1]

where μ is the dynamic viscosity of the test fluid [Ns/m²], K is the hydraulic conductivity of the test fluid [m/s], ρ is the density of the test fluid [kg/m³], and g is the gravitational constant [m/s²] (Freeze and Cherry 1979).

Therefore measurements of field-saturated hydraulic conductivity can be used to produce a value of permeability which is comparable to air permeability.

In field conditions, differences will arise between the value of permeability estimated from air and water flow measurements. Since water is a polar fluid, interactions may occur between the electrolytes in the water and exchangeable cations in the soil. Air flow through soil may cause drying and shrinking of the soil skeleton.

In order to use the simplified form of Darcy's law to quantify airflow in porous media, laminar flow conditions must be met. Deviations from Darcy's law can occur for air flow due to effects such as gas compressibility and slip flow. However if these effects are properly understood, the error incurred by maintaining a simple analysis is not significant.

A non-linear compressible flow equation should theoretically be used instead of Darcy's law for a compressible fluid. Kirkham (1946) quantified the effects of ignoring compressibility in air flow calculations. He developed a simple air permeameter to measure the permeability of soil in the laboratory and field using air pressure differentials which were very small relative to atmospheric pressure. The errors associated with neglecting compressibility for applied pressures of 25 cm and 50 cm H₂O were 1.25% and 2.5%, respectively (Kirkham 1946).

Slip flow occurs because gas velocities are generally nonzero at solid surfaces, resulting in an underestimation of flux according to Darcy's Law (Scanlon et al. 2002). Slip flow is also enhanced in fine-grained material with decreasing air-phase pressure (Ba-Te et al. 2005). Through in situ air permeability tests, Baehr and Hult (1991) found the error associated with ignoring slip flow became significant (> 10%) when permeabilities are in the range of $1 \times 10^{-12} \text{ m}^2$ or less.

3 EXPERIMENTAL METHODS

3.1 Prototype Design

Portable air permeameters have been used extensively to measure air permeability of shallow agricultural soils, typically to depths of 10 cm. A schematic of this method is found in Figure 3.

Air is supplied by a compressed gas cylinder, and its flow rate is measured by one of three flow meters of differing flow ranges. Air enters the soil within a metal cylinder that is pounded in to a shallow depth. To minimize air leakage along the inside boundary of the metal ring, the soil at this interface is kneaded carefully against the metal surface.

The inner volume of the cylinder is isolated from the atmosphere by the use of a packer, and the air pressure is measured with a water manometer. The air pressure entering the system is set to a value between 0.5 and 1 kPa with the pressure regulator valves on the outlet of the air tank.

A prototype air permeameter was constructed in 2005 and improvements were implemented for the 2006 field season. A photograph of the 2006 air permeameter design is shown in Figure 4. The entire process of air permeability measurements was completed by hand, since vehicle use on reclamation test covers was prohibited.



Figure 3. Portable air permeameter technique (from lversen et al. 2001).



Figure 4. Prototype air permeameter constructed for 2006 field season.

A drop hammer was used to insert a 16 cm metal cylinder to a total depth of 40 cm, with air permeameter measurements taken at each 10 cm depth increment. A plastic frame was used to support the cylinder during insertion. A commercial aluminum nitrogen tank was used for the air supply, and since the tank was pressurized to 2000 psi, it allowed for extensive testing before being depleted.

A plastic cap was fitted with ports for air flow to enter the cylinder and pressure to be measured. To ensure the cylinder was sealed from the atmosphere, a greased rubber gasket was used between the cap and cylinder surfaces, along with clamps to firmly attach the cap to the cylinder.

Similar to the schematic shown in Figure 3, pressure regulators, flow meters and a water manometer were used. These components were connected using plastic tubing, Teflon tape and fittings designed to ensure an air tight seal. A thermocouple, placed in the pressure measurement line was used to monitor temperature within the cylinder.

At each 10 cm depth increment, three measurements were taken, so that a linear relationship (i.e. Darcy flow) between flow rate and pressure gradient was ensured. Additional measurements were taken to investigate repeatability and leakage. On each soil cover, three complete profiles (10–40 cm depth) were completed in approximately two hours, highlighting the efficient nature of this method.

3.2 Data Analysis Method

To allow for operators with varying skill levels to use the air permeameter with minimal training, a simple analysis method such as applying a Darcy's law calculation over the length of the inserted column is advantageous. In this study, a numerical finite element analysis was performed on the data and compared to hand calculations using Darcy's law.

When applying Darcy's law only over the depth of the column it is assumed that the total pressure drop (Δp) occurs over the known length of a column (Δx). In fact, in the case of the air permeameter, the majority of the head loss occurs within the column. The reason for this is that the volume of this soil is relatively small, due to the confinement provided by the column, relative to the expanded flow path for air flow outside the column as it flows radially outward and back up towards the surface.

If the portion of pressure drop between the base of the column and atmosphere is ignored, some error will occur. By comparing Darcy's law calculations to numerical simulations, this error can be quantified and a correction factor provided to the operator.

The program SEEP/W (GEO-SLOPE International 2004) was used for the finite element numerical analysis, which simulates steady state water flow through saturated soil. The air permeameter was simulated using the unit weight of air instead of water, and steady state incompressible air flow was simulated in a saturated (constant K), axisymmetric flow system.

An example of an air permeameter simulation is shown in Figure 5. Null elements of zero hydraulic conductivity were used to represent the cylinder wall. Total head [m] boundary conditions equivalent to the measured air pressure and zero atmospheric pressure were applied to the ground surface inside and outside the cylinder, respectively.

The value of K within the model (K_{model} [m/s]) was set to a value of unity. A boundary flux (Q_{model} [m³/s]) was calculated through the cross-sectional area of the column. As flow and hydraulic conductivity are directly

proportional for a given test geometry, the actual hydraulic conductivity (K_{actual} [m/s]) was calculated from the following equation:

$$Q_{actual}K_{model} = Q_{model}K_{actual}$$
[2]

where Q_{actual} [m³/s] is the recorded flow rate from an air permeability test. The hydraulic conductivity using air as the test fluid, K_{actual}, was then converted to a value of permeability using Equation 1.



Figure 5. SEEP/W model of an AP test in a uniform material: (a) finite element mesh; and (b) resultant total head contours.

3.3 Laboratory Testing

Laboratory testing was initiated for two reasons. The first reason was to verify that permeabilities measured using air and water as the test fluids are equal at identical fluid phase contents. The second reason was to determine if the prototype air permeameter could produce a value of permeability equivalent to that measured using a conventional constant head column test.

A plastic rigid wall permeameter filled with dry, uniform sand was used for the permeability tests. An air permeability test was performed first, using the pressure regulator, flow meters and water manometer from the prototype design. Darcy's law was used to calculate the permeability of the sand using the properties of air.

The column was then saturated with water, and a permeability test conducted according to ASTM D2434-68 Standard Test Method for Permeability of Granular Soils (Constant Head) (American Society for Testing and Materials 2005). Photographs of the column tests for both air and water are shown in Figure 6.

A tank of the same dry, homogeneous sand was used for the full scale test. The air permeameter was inserted to a full depth of 40 cm, and three readings of pressure and flow were taken at each 10 cm depth increment. The boundary effects created by the tank walls were taken into consideration during analysis. The full scale laboratory test is shown in Figure 7.



Figure 6. Column permeability tests using (a) air as the test fluid; and (b) water as the test fluid.



Figure 7. Full scale laboratory tank test of air permeameter.

3.4 Field Trials

The air permeameter was tested on three different reclamation soil cover prescriptions. Schematics of the cover prescriptions are shown in Figure 8. The objective of the field trials was to determine how well the air permeameter performed in field conditions, and compare the results to the Guelph permeameter.

The primary test site was the SW30 Dump at Syncrude Canada Ltd. Three prototype reclamation covers consisting of a peat-mineral mix overlying till secondary material were placed in 1999 over saline sodic overburden shale. The covers were each 1 ha plots of 35 cm, 50 cm and 100cm thick layered covers. The 2006 air and Guelph permeameter testing took place on the D3 cover, which consisted of 20 cm of peat-mineral mix over 80 cm of till secondary.



Figure 8. 2006 field trial cover prescriptions: (a) Syncrude SW30 Dump, (b) Syncrude Coke Beach, and (c) Suncor Coke Stockpile.

The second test site was a deposit of petroleum coke at Syncrude Canada Limited, referred to as the Coke Beach. Two prototype covers, 35 cm and 100 cm thick, were constructed of a peat-mineral mix overlaying till secondary. The air and Guelph permeameter tests in 2006 were conducted on the 100 cm cover, which was 20 cm of peat over 80 cm of till.

The third test site was at Suncor Energy Ltd., and also involved reclamation of petroleum coke. At this site two covers of varying thicknesses of peat-mineral mix overlying tailings sand were used. The air and Guelph permeameter tests were conducted on the shallow cover, consisting of 30 cm of peat-mineral mix overlying 35 cm of tailings sand.

3.5 Test Cover Material Properties

Material properties for all cover materials have been characterized. The peat/mineral mix summarized below is representative of all three sites. The till/secondary material is representative of both of the Syncrude sites. The properties of the sand layer (tailings sand) within the Suncor Coke Stockpile cover are also discussed.

Particle size distributions of the till/secondary material were completed in 2000 for three depths within the SW30D cover: 0-20 cm, 20-50 cm and 50-100 cm, as shown in Figure 9. The till/secondary material was 37% sand, 42% silt, and 21% clay particles (Kelln et al. 2008). PSD analysis was not performed on the peat/mineral mix because the organic fraction of the peat floated during the wet sieving process instead of passing through the sieve (Boese 2003).

A particle size distribution was also conducted on a sample of tailings sand in 2003. Test results were provided by MDH Environmental Solutions Laboratory, as shown in Figure 9. The average PSD of the tailings sand was 93% sand and 7% fines (silt and clay).



Figure 9. Particle size distribution for till/secondary material (Boese 2003) and tailings sand.

Soil water characteristic curves were determined for the peat/mineral mix and till secondary by Boese (2003) through laboratory testing. The soil water characteristic curve for the tailings sand was determined in 2003 through laboratory testing at MDH Engineered Solutions. Results from these tests are found in Figure 10.



Figure 10. Soil water characteristic curve for peat/mineral mix and till/secondary materials (Boese 2003), as well as tailings sand.

4 RESULTS AND DISCUSSION

Results from the laboratory and field trials described in Section 3 are presented here. All air permeability test data are presented using the method of box plots. The range of data between the first and third quartiles (interquartile range) is displayed by the box, with the bar through the inside of the box representing the median data value. Outliers are represented by the symbol "o" and extreme outliers are represented by "*".

4.1 Laboratory Test Results

Results from the laboratory tests are presented in Figure 11. The median permeability values measured using the air and water column tests are 7.9 x 10^{-11} m² and 7.6 x 10^{-11} m², respectively. The relative difference of 4% between these values supports the theory that under ideal conditions, the permeability of soil to air or water is approximately equal.



Figure 11. Comparison of intrinsic permeability measurements using a column with air as the test fluid, a column with water as the test fluid, and the AP in a sand tank, where (n) is number of tests.

The median value of permeability determined through the full scale air permeameter test was $9.2 \times 10^{-11} \text{ m}^2$. This value has a relative difference of 21% from the water column test. In terms of the objectives of this research program, this error is acceptable for using the air permeameter to predict permeability of a uniform soil.

4.2 Field Trial Results

Results of air permeability and Guelph permeameter tests on the three cover prescriptions are discussed in Table 1 and shown in Figure 12. The air permeability values presented were determined from back analyses using the numerical method described in Section 3.2. The Guelph permeameter values were determined by converting the measured hydraulic conductivities to permeability using Equation 1.

Since the average thickness of peat-mineral mix on the Suncor Coke stockpile cover was 30 cm and the total cylinder insertion included 10 cm or less of tailings sand, the results for the Suncor site are representative of the peat mineral mix. The thickness of the peat-mineral mix on both of the Syncrude soil covers was found to be only a few centimetres thick. On the SW30 Dump this could be caused by inconsistent cover placement, whereas on the Coke Beach this is likely due to wind erosion. Therefore the results reported are primarily representative of the till rather than the peat-mineral mix.

Depth	Suncor Coke	SW30 Dump	Coke Beach
/Test	k [m²]	k [m²]	k [m²]
10 cm	4.9 x 10 ⁻¹²	4.0 x 10 ⁻¹¹	1.2 x 10 ⁻¹⁰
20 cm	2.9 x 10 ⁻¹²	6.8 x 10 ⁻¹¹	1.0 x 10 ⁻¹⁰
30 cm	5.0 x 10 ⁻¹²	7.8 x 10 ⁻¹¹	1.0 x 10 ⁻¹⁰
40 cm	4.3 x 10 ⁻¹²	6.6 x 10 ⁻¹¹	1.4 x 10 ⁻¹⁰
GP	3.5 x 10 ⁻¹³	2.8 x 10 ⁻¹³	8.5 x 10 ⁻¹³

Table 1. Results summary of 2006 air and Guelph permeameter field trials.



Figure 12. Comparison of values of permeability for all materials tested using the AP and water column in the laboratory or GP in the field, where (n) is the number of tests.

4.3 Discussion of Results

The values of permeability in Figure 12 include the air permeameter results from all depth profiles in all trials. Comparative permeability values determined by the water column method in the laboratory and Guelph Permeameter in the field cases are also shown.

As discussed in Section 4.1, the laboratory results show that there is very little difference in permeability values measured using air or water as the test fluid under ideal conditions. This suggests that the air permeameter technique does provide a reliable measurement of permeability.

There is a difference of approximately one order of magnitude in the median values of permeability measured with the air and Guelph permeameter methods for the peat-mineral mix at the Suncor Coke Stockpile cover. The Suncor soil cover was found to be dry and fairly uniform in terms of soil structure. One explanation for this variance may be the large difference in surface area available to flow between the two methods. The diameter of the Guelph well bore was 6 cm, where the diameter of the air cylinder was 16 cm. Another explanation could be air entrapment. As discussed earlier, effects such as air entrapment during infiltration are also known to create underestimates of saturated hydraulic conductivity when using the Guelph permeameter (Reynolds and Elrick 1986).

The median values of permeability for the air and Guelph permeameters at the two Syncrude till covers were consistently two orders of magnitude different. The material in these covers was predominantly fine-grained with an extensive macropore network as a result of weathering. This macropore network was formed predominantly in the vertical direction, creating anisotropy within the soil.

The presence of anisotropy within the soil affects both tests differently. Since the air permeameter measures flow in the vertical direction it captures the maximum permeability of the soil. It also utilizes a large undisturbed surface area which allows the entire macropore network to be used for air flow. The Guelph permeameter measures an average of vertical and horizontal flow, and is therefore affected by the lower horizontal permeability.

During a Guelph permeameter test, the flow dominating macropores can be sealed off, decreasing the surface area of the well bore available to flow and causing an underestimation of K_{fs} . This may be caused by smearing of the fine-grained materials while augering the well bore or perhaps swelling of the clay particles during saturation. One possibility causing an overestimation in air permeability is the effect of slip flow.

5 CONCLUSION

Tracking the changes in hydraulic conductivity is an important step in predicting the long term performance of a reclamation soil cover. The method of air permeability could potentially be a viable alternative to traditional methods of field saturated hydraulic conductivity measurement. However, further investigation is required before the method can be determined reliable.

The air permeameter was found to provide an acceptable value of permeability under ideal, controlled conditions. However, with increasing anisotropy and heterogeneity, the difference between permeabilities measured using the air and Guelph permeameters increased substantially.

A difference of one order of magnitude between permeability predictions can be explained by factors such as difference in surface area available to flow and air entrapment during infiltration using the Guelph permeameter. However, a difference of two orders of magnitude between permeabilities predicted for till soil covers is not acceptable.

Several factors were discussed throughout this paper which may contribute to the difference in permeabilities. Some of these factors include macropore flow, air entrapment, sample size, flow geometry, smearing of fine grained materials, and slip flow. Understanding of these factors could possibly be gained by comparing the air permeameter to other methods of saturated hydraulic conductivity measurement.

If improvements to the air permeameter system were made as well as confidence gained in the system, the air permeameter could then be used in more extensive applications, such as mapping the spatial distribution of permeability across a reclamation cover. However, if the goal of the air permeameter is not to provide an absolute value of permeability but track changes over time it does hold strong potential as a reclamation monitoring tool.

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