Modeling the flow of oil sands process-affected water in clay till formation

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ABSTRACT
Process-affected water from oil sands operations in Canada is managed via storage in constructed tailings ponds. These ponds are generally built on clay till formation due to low permeability. The objective of this research is to characterize the hydraulic properties of the clay till and develop a predictive model to examine the tendency of process-affected water to migrate into underlying groundwater channels. An infiltration experiment was conducted using a double ring infiltrometer. A model of flux into the clay till under a steady state condition was also completed using hydraulic conditions that reflect pond filling conditions. Field and modeling results indicated that the clay till has very low permeability that can significantly prevent the movement of process-affected water in the tailing pond foundation.

RÉSUMÉ
L'eau de processus-affecté des opérations de sables de pétrole est géré au Canada via l'emmagasinage dans les étangs de queues construits. Ces étangs sont généralement construits sur l'argile jusqu'à la formation en raison de la perméabilité basse. L'objectif de cette recherche est de caractériser les propriétés hydrauliques de l'argile jusqu'à ce qu'et développe un modèle prophétique pour examiner la tendance d'eau processus-affecté pour migrer dans les chaînes d'eau souterraine fondamentales. Une expérience d'infiltration a été dirigée l'utilisation d'un double infiltrometer d'anneau. Un modèle de flux dans l'argile jusqu'à ce que sous une condition de l'état constante a été aussi complété l'utilisation conditions hydrauliques qui reflètent les étangs remplissant des conditions. Les résultats de champ et modelage ont indiqué que l'argile jusqu'à ce qu'a une perméabilité et un débits très bas qui peuvent empêcher significativement le mouvement de processus eau affectée dans le suit la fondation d'étang.

1 INTRODUCTION

Alberta, Canada is home to one of the largest oil deposits in the world, with over 173 billion barrels of proven recoverable oil, by current technologies, available in three major deposits in the northeast corner of the province (Alberta Government 2008). Surface mining occurs in the Athabasca oil sands deposit, north of the community of Fort McMurray and on the banks of the Athabasca River, and to date, over 530 km^2 of land has been disturbed (Alberta Government 2008).

The hot water extraction process utilized in the oil sands industry results in the consumption of large volumes of water and the consequential production of tailings. Tailings consist of process-affected water: alkaline, slightly brackish and acutely toxic water with significant volumes of settling and non-settling soil fines (Allen 2008). Proper management of oil sands process-affected water is imperative to reduce the possibility of release into surface and ground water. Regulatory bodies enforce a policy of zero discharge for the oil sands industry, resulting in large storage impoundments, or tailings ponds (Allen 2008).

Due to the operational necessities in the oil sands industry, out-of-pit tailings ponds are constructed to contain the tailings and process-affected water. There are a number of locations on oil sands leases where the tailings ponds will be sited over buried sand channels, relict from previous glacial rivers. The extent of process-affected water seepage from these tailings ponds into underlying sand/groundwater channels is poorly understood. Therefore, a collaborative research effort was initiated between an oil sands operator and University of Alberta to examine the hydrogeological and flow properties of clay till material, the foundation stratum of a recently constructed tailings pond in the Athabasca oil sands deposit, north of Fort McMurray, Alberta, Canada. This newly constructed tailings pond lies on top of surficial deposits of organic soil, up to a depth of 4m, underlayed with an 8-15m clay till deposit, with varying silt and sand lenses. A sand and gravel channel (up to 30m deep) exists below the clay till and is incised into the Clearwater Formation, and in places through the Clearwater into the underlying McMurray Formation which contains the oil sands.

Different soil properties were identified in this study and used to produce a model that predicts the seepage into the sand channel. The study investigated different parameters including hydraulic conductivity, infiltration rates, and variation of ground pore water pressure and suction due to local groundwater movement and the temporal variations in groundwater table (Fredlund et al. 2002, De Vries 1972, Magesan et al. 1999). The clay till was analyzed using saturated/unsaturated soil properties combined with a field infiltration study. The analysis allowed predicting the flow of process-affected water through the low permeability soil and the potential for groundwater contamination.

2 METHOD AND MATERIALS

2.1 Infiltration Experiment

To assess the infiltration rate of oil sands process-affected water into the clay till under saturated conditions, a 10m x 10m x 2m pond was excavated in the clay till and an in-pit infiltration experiment was performed in the summer of 2008 using a closed double ring infiltrometer. The experimental set up consisted of two rings that are 33 and 64 cm in diameter, both 50 cm in height. The rings were pushed 15cm in to the clay till and attached to two manometers of diameter 9 and 17 cm for measuring changes in the hydraulic head. Calibration of the manometers indicated that for each 1 cm change in head, there is 63.64 and 227.07 cm^3 volumetric flow through the inner and outer rings, respectively.

The rings were filled with water and, initially, manometer readings were taken at hourly intervals along with observations of change in soil, water and air temperature. Preliminary analysis suggested insignificant change in infiltration of water at the hourly interval; therefore temporal changes in water level were recorded every 24 hours. Moisture content of the soil was determined using gravimetric analysis. The in-pit infiltration experiment was conducted in duplicate and the final moisture content of the soil sample after 12 days of continual ponding was determined as a measure of the saturated moisture content.

The infiltration rate was estimated based on the change in head using the obtained calibration values, over time. Hydraulic conductivity was determined via falling head permeability test based on Darcy's law (Das 2005). Five values of saturated infiltration rate and hydraulic conductivity were calculated and averaged once steady state conditions were reached.

2.2 Flow Modeling in the Clay and Sandy Till

Soil characteristics obtained from soil grain size distributions are important in assessing soil hydrological properties (Pachepsky and Rawls 2004) and essential for proper modeling. Hence, five soil core samples were taken at depths of 3m (S3a and S3b), 5m (S5), 6m (S6) and 9m (S9), all in the clay till formation from the oil sands lease site.

The sedimentation test (ASTM D22-54T) was utilized to obtain the grain size distribution for all samples. The grain size data was analyzed using Soil-Vision (Fredlund et al. 2003). The grain size distributions were fit to both unimodal and bimodal functions. The fit with the best correlation, as indicated by high r^2 values, was used to estimate the fine fractions of the soil samples (Fredlund and Rahardjo 1993, Pham and Fredlund 2008).

Using the plastic limit, liquid limit and the grain size distribution data, the soils were classified using the Unified Soil Classification System (ASTM D2487). The soil-water characteristic curves (relationship between water content of unsaturated soil and suction) for each of the five soil samples were estimated using the soil volume-mass properties and grain size distribution data (Fredlund et al. 1997). The soil-water characteristic curve was utilized to estimate design parameters such as air-entry values and residual water content. These values in turn were used with the Fredlund and Xing (1994) equation (Equation 1) to determine the variation in hydraulic conductivity as a function of soil suction.

$$k = k_{sat} \frac{\int_{\psi}^{\psi_s} \frac{\theta(y)-\theta(y)dy}{y^2}\theta'(y)dy}{\int_{\psi_{aev}}^{\psi_y} \frac{\theta(y)-\theta_s}{y^2}\theta'(y)dy} \qquad [1]$$

Where: k = hydraulic conductivity (cm/hr)
k_{sat} = saturated hydraulic conductivity (cm/hr)
ψ = suction
ψ_{aev} = air entry suction value of the soil
θ = volumetric water content
θ_s = saturated volumetric water content

Other clay till volume-mass parameters were determined based on: 100% degree of saturation, 0.18 (g/g) gravimetric moisture content and particle density of 2.63 g/cm^3 (Klohn Crippen Consultants Ltd. 2004). Parameters determined include soil porosity, void ratio, volumetric water content, soil unit weight and total density. Examination of natural moisture content data of the clay till during the infiltration experiment and from 336 borehole data from drillings within the region confirmed the maximum gravimetric moisture content in the clay till was 20% (Klohn Crippen Consultants Ltd. 2004), therefore the changes in the clay till volume-mass parameters were determined by varying the gravimetric moisture content between 0 and 20%.

SVFlux (Soil Visions System Ltd. 2008), a saturated and unsaturated finite element, two- and three-dimensional seepage modeling software, was used to define the model geometry. A steady state model analysis was carried out to determine the instantaneous flow rate through 9m of the clay till profile that underlays the constructed pond. The model geometry consisted of a two-dimensional finite element space, with boundary conditions of annual recharge rate of 17mm/year and total head of 367.2, simulating elevation head and expected water level in the tailings pond (Figure 1). A clay till material, representing the soil in the region, was used in the model to determine the flux through the 9m profile. The model generated water flux profiles in vertical and lateral directions in the 9m deep clay till.

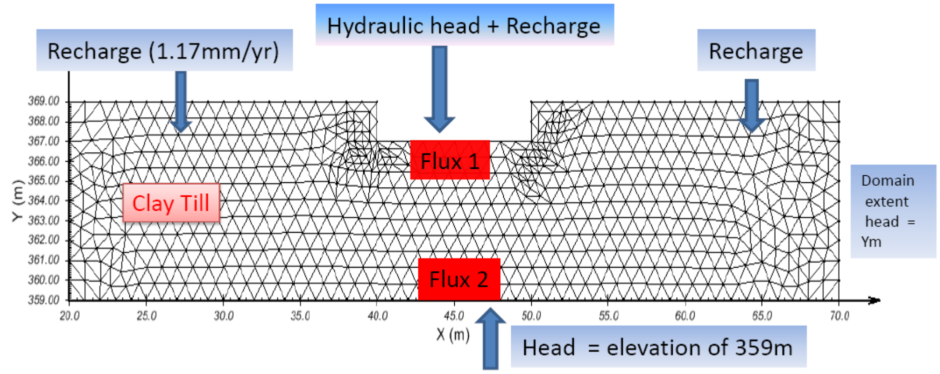

Figure 1. Schematic of the water infiltration model

3 RESULTS AND DISCUSSION

3.1 Infiltration Experiment

A closed, double ring infiltrometer experiment conducted between the 16 and 25th of August, 2008 indicated that the infiltration rate through a 15 cm clay till profile ranged from 4.17 x 10^{-3} to 2.92 x 10^{-2} cm^3/cm^2hr. The average saturated infiltration rate into the clay till after seven days of ponding is 2.14 x 10^{-2} cm^3/cm^2hr (CV =25.8%, n = 6). The soil gravimetric moisture content ranged between 15 to 20.5 % (g/g). The last five measurements taken during the infiltrometer experiment were utilized to calculate an average hydraulic conductivity of 3.04 x 10^{-9} m/s (CV = 26.1%, N = 5).

These results confirmed that the clay till is a low permeability layer that can significantly reduce the seepage of oil sands process-affected water from tailings ponds into the groundwater. The low coefficient of variation (CV) in the hydraulic parameters presented (< 30%) in comparison to high coefficient of variation values usually associated with hydraulic parameters also increases the confidence in the ability of clayey materials to retain significant amount of water and with less spatial variability in water content in saturated conditions (El Idrysy and De Smedt 2007).

Through the course of the experiment, the soil and water temperatures ranged between 18 and 25°C and the air temperature reached a maximum of 36°C. Although variation in soil and water temperature could influence the movement of water into and through the clay, significant variations in flow rate into the clay till were not observed as indicated by the CV values of the obtained measurements (<30%). Comparing the inner and outer ring flow data shows high flow rates through the outer ring, which suggest significant lateral movement of water rather than vertical infiltration due to the low hydraulic conductivity of the clay till. This is in agreement with findings of a previous seepage experiment in clay (Hendry et al. 2004).

3.2 Soil Properties

Analysis of the clay till volume-mass parameters with changes in soil gravimetric moisture content provide valuable information about the nature of the clay till in the saturated condition. The total unit weight, dry density and total density of the clay till reduce with increasing moisture content. This indicates that the clay till has a swelling nature. This observation is further supported by the increase in volumetric moisture content, void ratio and porosity with increasing moisture content. Figures 2, 3 and 4 show the impact of moisture content in the clay till on a number of soil parameters.

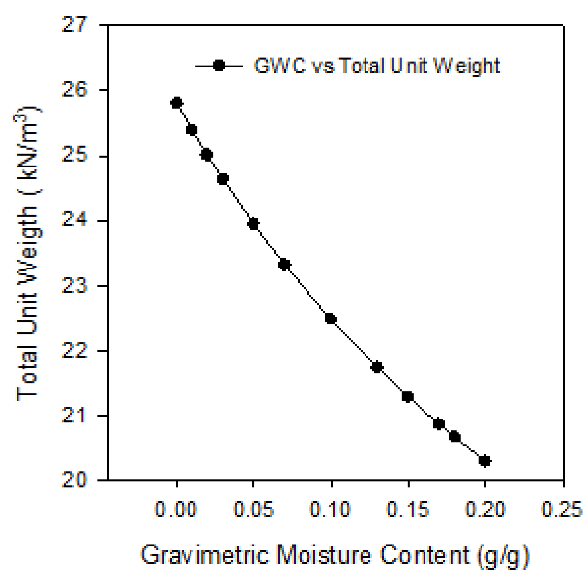

Figure 2. Impact of moisture content on soil unit weight

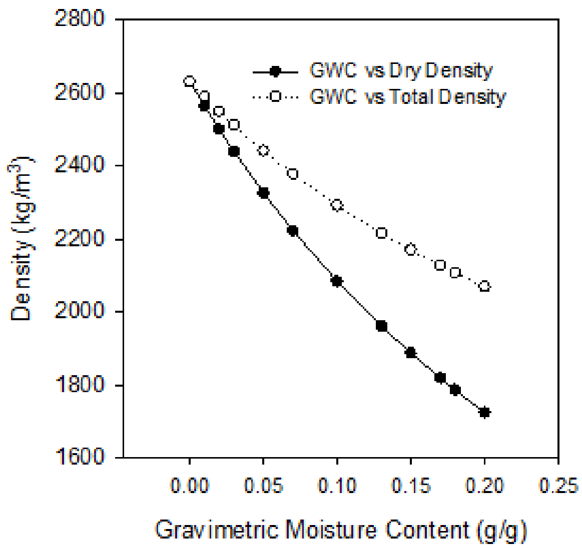

Figure 3. Impact of moisture content on soil density

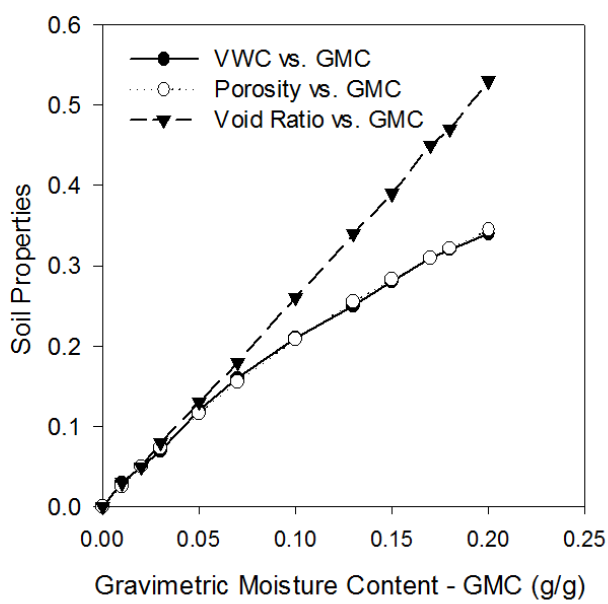

Figure 4. Impact of moisture content on volumetric water content, porosity and void ratio

Five samples of the clay till taken at depths ranging from 3 to 9m were analyzed for grain size distribution in the fine particles (sizes <75µm). Hydrometer analysis showed that the clay composition varied from 27 to 33% of the soil mass, 42 to 56% was silt, and 11 to 31% was sandy materials. The soils' plastic limit ranged from 14 to 18%, liquid limit from 25 to 33% and the plasticity index ranged from 8 to 17%. The soils were generally in the clay loam (CL) range of the Unified Soil Classification System. This data is summarized in Table 1.

Table 1. Physical properties of selected clay till samples

Sample:	S3a	S6	S9	S3b	S5
Properties					
Depth (m)	3	6	9	3	5.5
Liquid Limit (%)	25	33	26	29	26
Plastic Limit (%)	17	16	18	17	14
Plasticity Index (%)	8	17	8	11	13
Classification	CL	CL	CL	CL	CL
Grain Sizes (USCS)					
% Clay	33.5	28.0	26.4	33	33
% Silt	44.5	54.2	42.4	56	56
% Sand	22.0	17.9	31.2	10.8	11

Analysis of grain size distribution data (Figure 5) for the soil produces the best theoretical fit with the bimodal function ($r^2 > 0.98$). Some of the relevant bimodal fitting parameters include the initial breaking point of the curve (0.933 ± 2.13), steepest point of the slope (0.834 ± 0.45), shape of the curves (6.32 ± 2.55), residual particle diameter (0.01mm), and D_{10} ($3.11 \times 10^{-5} \pm 2.37 \times 10^{-5}$), shown in Figure 5. The bimodal grain size distribution along with the field estimate of saturated hydraulic conductivity were used to produce the soil-water characteristics curve, from which the permeability and storage functions (Figure 6) were estimated and used subsequently in the model.

The obtained soil-water characteristic curves allow identifying air-entry values (108.10 ± 11.07 kPa), and residual water content of 3.1 ± 0.00037%. The suction at which residual water content occurs was estimated at 77596.08 ± 3.55 E04 kPa.

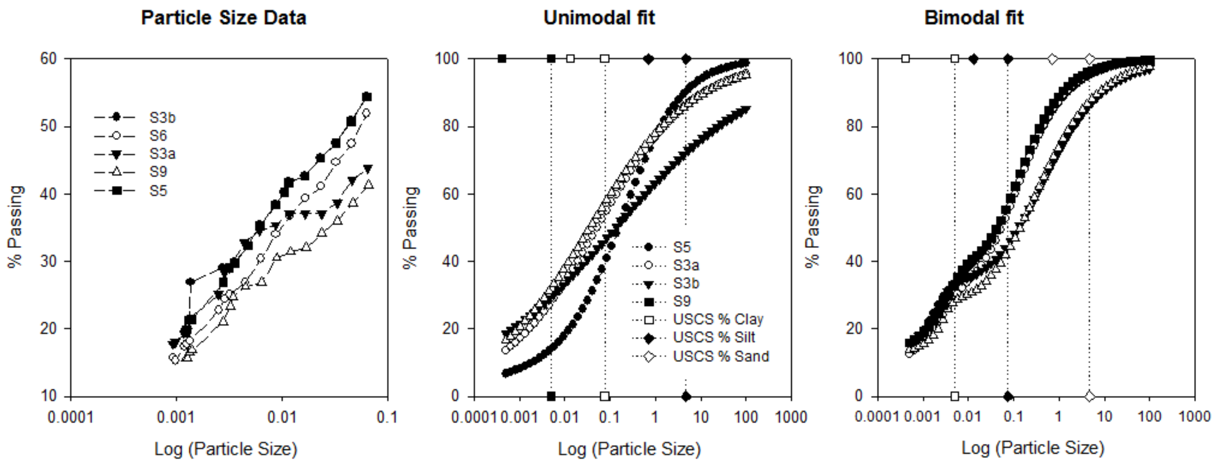

Figure 5. Particle size distribution of the clay till with the unimodal and bimodal fit used for estimation of soil property functions.

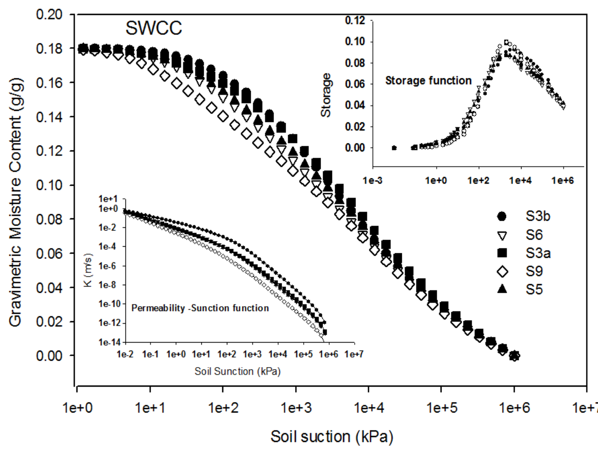

Figure 6. Soil-water characteristic curve, storage and hydraulic conductivity functions.

3.3 Flow Modeling in Clay Till

To investigate the flow properties of the clay till, a numerical model was generated using a finite difference package in Soil Vision. The model accounts for the clay till characteristics and behavior functions obtained from field data, as well as subsurface nature. The model geometry is shown in Figure 1. The flow patterns into two locations were investigated: at the bottom of the pond (designated by Flux1) and at the bottom of the 9 m deep clay till deposit (designated by Flux2). Flux rate (meter/year) at the two were obtained over 500 years at the bottom of the pond and the base of the clay till, or above the sand channel.

Estimates of the fluxes in steady state flow through the clay till are presented in Figures 7a-b. Flux distribution in the horizontal direction in figure 7a indicates that flux rates are not expected to exceed 0.01 m/year at the base of the pond even after more than 500 years of water ponding. No horizontal flux component is expected to exist. Figure 7b demonstrates expected flux in the in the clay till in the vertical direction. The maximum vertical flux is not expected to exceed 0.1 m/year at the bottom of the pond or the clay till deposit even after more than 500 years. Negative flux values in Figures 7a and 7b indicate lateral flux in the negative direction and percolation, respectively. Results in Figure 7a-b confirm that there is insignificant flow in the clay till, which agrees with the insignificant infiltration rates obtained from the field study. Similarly, a previous study that used isotope analysis has also concluded that clay formations can prevent seepage flow (Hendry et al. 2004). Jang (2000) and Lavastre et al. (2005) also observed the same low or insignificant flow and infiltration rates in soils with low permeability.

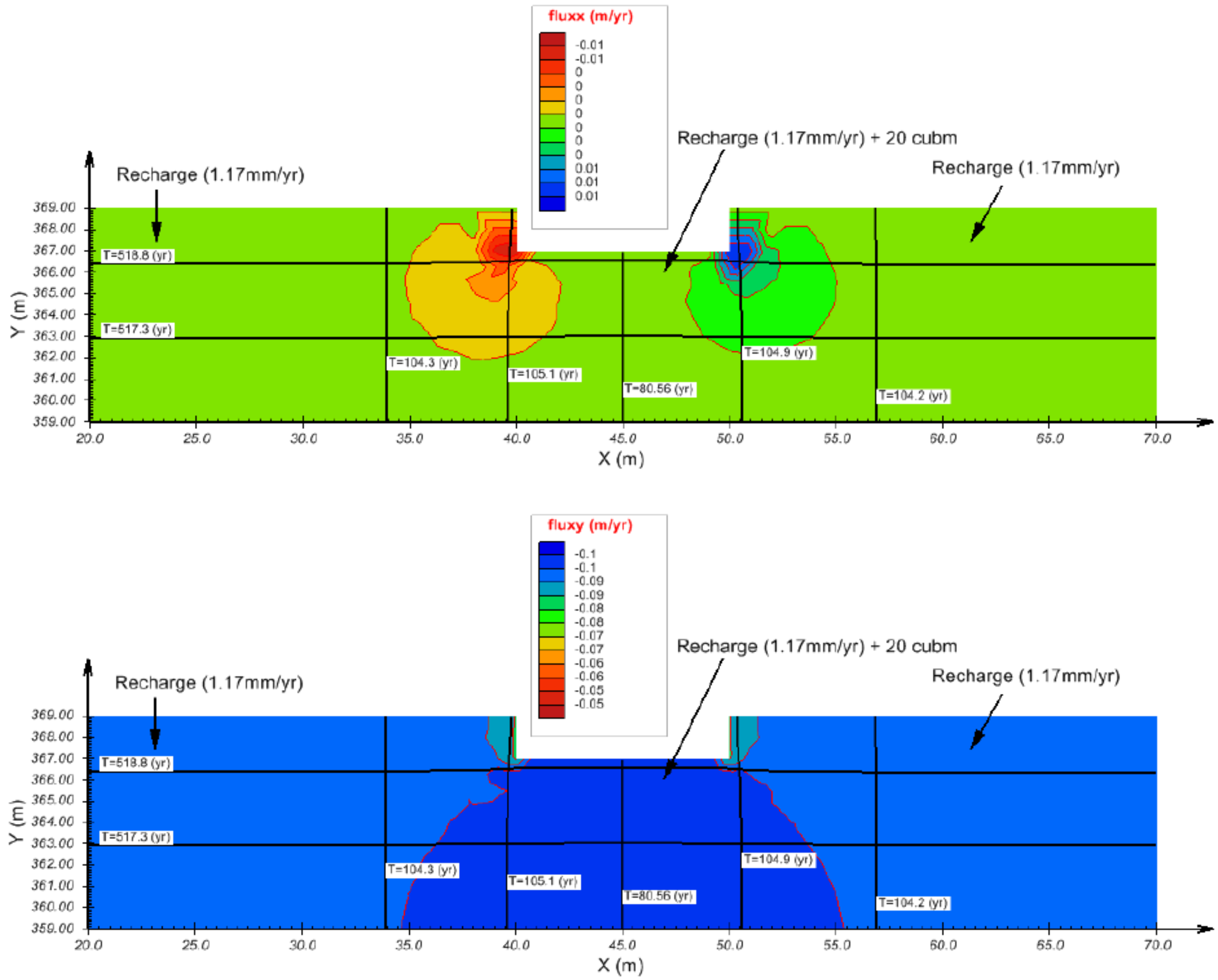

Figure 7a (top) and b (bottom). Flux estimates in the clay till in the horizontal and vertical direction, respectively, at the bottom of the pond and the base of the clay till deposit.

4 CONCLUSION

The infiltration experiment and associated numerical modeling confirmed that the flow through a saturated profile of the tailing pond clay till is little or insignificant. The clay till can significantly prevent the movement of process affected water in the tailing pond foundation where present extensively. More research will also be required to assess the impact of salts, process-affected water chemistry and clay till mineralogy on the flow characteristics and structural stability of the clay materials.

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REFERENCES

Alberta Government. 2008. *Alberta oil sands: resourceful. responsible.* Edmonton, AB.

Allen, E.W. 2008. Process water treatment in Canada's oil sands industry: I. Target pollutants and treatment objectives. *Journal of Environmental Engineering and Science* **7**: 123-138.

Das, B.M. 2005. *Fundamentals of Geotechnical Engineering*, 2nd Ed. Nelson, Toronto, ON.

De Vries, J. (1972). Soil infiltration of wastewater effluent and the mechanisms of pore clogging. *Journal of Water Pollution Control Federation* **44**: 565–573.

El Idrysy, E.H. and De Smedt, F. 2007. A comparative study of hydraulic conductivity estimations using geostatistics. *Hydrogeology Journal* **15(**3): 459-470.

Fredlund, M.D., Fredlund, D.G., Houston, S.L., and Houston, W. 2003. Assessment of unsaturated soil properties for seepage modeling through tailings and mine wastes. *Tailings and Mine Waste '03*. Swets & Zeitlinger, Lisse.

Fredlund, M.D., Wilson, G.W., and Fredlund, D.G. 2002. Use of the grain-size distribution for estimation of the soil-water characteristic curve. *Canadian Geotechnical Journal* 39:1103-1117.

Fredlund M,D, Wilson, G.W. and Fredlund, D.G. 1997. Prediction of the soil-water characteristic curve from grain-size distribution and volume-mass properties. *Proceedings of the 3rd Symposium on Unsaturated Soil*, Rio de Janeiro, Brazil, 13-23.

Fredlund, D.G. Fredlund, D.G and Xing A. 1994. Equations for the soil-water characteristics curve. *Canadian Geotechnical Journal* **31**: 521-532.

Fredlund, D.G., and Rahardjo, H. 1993. *Soil mechanics for unsaturated soils*. John Wiley & Sons, Inc., New York.

Hendry, M.J., Kelln, C. J., Wassenaar, L. I., and Shaw, J. 2004. Characterizing the hydrogeology of a complex clay-rich aquitard system using detailed vertical profiles of the stable isotopes of water. *Journal of Hydrology* **293**: 47-56.

Jang, S.Y. 2000. Analysis of flow behavior in a landfill with cover soil of low hydraulic conductivity. *Environmental Geology* **39**: 292-298.

Klohn Crippen Consultants Ltd., 2004. *Suncor Energy Inc. Millennium Mine: Design of South Tailings Pond Final Report*. Calgary, AB.

Lavastre, V., Jendrzejewski, N., Agrinier, P., Javoy, M., and Evrard, M. 2005. Chlorine transfer out of a very low permeability clay sequence (Paris Basin, France): ^{35}Cl and ^{37}Cl evidence. *Geochimica et Cosmochimica Acta* **69**(21): 4949-4961.

Magesan, G.N., Williamson, J.C., Sparling, G.P., Schipper, I.A., and Llioyd-Jones, A.Rh. 1999. Hydraulic conductivity in soils irrigated with wastewaters of differing strengths: Field and laboratory studies. *Australian Journal of Soil Research* **37**: 391–402.

Pachepsky, Y. and Rawls, W.J. 2004. *Development of pedotransfer functions in soil hydrology*. Elsevier Science, Amsterdam.

Pham, H.Q., and Fredlund, D.G.. 2008. Equations for the entire soil-water characteristic curve of a volume change soil. *Canadian Geotechnical Journal* **45**(4): 443-453.