A methodology for evaluation of the performance of soil liners using the mechanics of saturated and unsaturated soils

Joel Mateo
DST Consulting Engineers, Inc – Thunder Bay, Ontario, Canada
Sai K. Vanapalli
Civil Engineering Department – University of Ottawa, Ottawa, ON, Canada
Mostafa Warith
Civil Engineering Department – University of Ottawa, Ottawa, ON, Canada

ABSTRACT
Most engineered landfills are placed over natural clay or compacted clay liners. The key guidelines suggested for the clay liners by the environment regulatory agencies include achieving a hydraulic conductivity value equal to 1 x 10^{-9} m/s or lower and to have a liner thickness in the range of 0.75 m. This project aims to evaluate the performance of a proposed compacted clay liner to be constructed using two different clayey soils following the Ontario Landfill standards (Reg. 232/98) of the Ontario Ministry of Environment. In addition, comparisons are provided with the performance of the liner using another methodology proposed in this paper that is based on the mechanics of saturated and unsaturated soils and computer modeling studies taking account of the influence of climate. The study shows that the compacted clay liner thickness can be designed using the methodology presented in this paper. It is also recommended to include surveillance and monitoring regulations of the unsaturated/vadose zone of the clay liner ensuring a better quality performance and long term use.

RÉSUMÉ
La plupart des enfouissements des terres sont placés au-dessus de l'argile naturelle ou des recouvrements compacts d'argile. Les directives principales suggérées pour les recouvrements d'argile par les organismes de normalisation d'environnement incluent réaliser une valeur de conductivité hydraulique équivalente à 1 x 10^{-9} m/s ou mineure et d'avoir une épaisseur de recouvrement dans la gamme de 0.75 m. Ce projet vise à évaluer l'exécution d'un recouvrement compact proposé d'argile construit avec deux sols argileuses différents en utilisant les normes de enfouissements de terres d'Ontario (Reg. 232/98) du Ministère de l'Environnement d'Ontario. En addition, des comparaisons sont données avec d'exécution du recouvrement en utilisant une autre méthodologie proposée en cet article qui est basée sur les mécanismes des sols saturés et insaturés et des logiciels modelant en tenant compte de l'influence du climat. L'étude prouve que l'épaisseur de recouvrement d'argile compacte peut être conçue en utilisant la méthodologie présentée. On recommande également d'avoir la surveillance et des règlements de contrôle de la zone insaturée du recouvrement d'argile assurant une exécution de meilleure qualité et une utilisation à long terme.

1 INTRODUCTION

Soil liners are used as barriers to prevent the migration of pollutants into natural resources. In engineering practice, naturally available clay is compacted in a single or multiple layers to serve the function of a soil liner. Natural clays or other fine-grained soils are preferred as soil liners because of their ability to impede the flow of water due to their low hydraulic conductivity (Fonstad et al, 1999; Benson, 2000). They are also capable to adsorbing the total dissolved solids (TDS) in the leachate (Bagchi, 1987). Fine-grained clayey soils are also preferred because of their availability locally in many regions or at a relatively low cost. In addition, positive and extensive experience of using fine-grained clayey soils in several geotechnical structures such as earth dams for several decades has encouraged the use of fine-grained soils as candidate materials for soil liners.

The early soil liners used in engineering practice consisted of a single compacted clay liner without a leachate collection system (Benson, 2000). However, more recent soil liners have leachate collection systems incorporated in their design. The most common liner system consists of a clay liner overlaid by a sand layer. The thickness of the clay liner can vary from location to location and the nature of the project depending on the soil properties from as thin as 0.15 m to as thick as 4 m (Benson, 2000).

In the present study, two clay samples from different locations of the National Capital Region (Ottawa-Gatineau) are examined for their suitability as candidate materials for soil liners. The first sample was collected from the area of Aylmer, Gatineau and the second from Rideau region of Ottawa. The Ottawa region is located on the Champlain Sea Basin, which is part of the Ottawa-St. Laurent lowland area (Gadd, 1988). The region typically has Champlain Sea clay deposits with reasonably uniform properties; however, the properties of the two clays differ because they are collected mainly from surficial deposits that may have been subjected to different sedimentations events and likely invasion of marine water which may have occurred during the Pleistocene age (Bélanger,1998).

An attempt is made through this project to evaluate the performance of a single composite liner designed following the Ontario Landfill standards (Reg. 232/98) of Ontario

Ministry of Environment and compare it with a new methodology proposed using the mechanics of saturated and unsaturated soils taking account of the influence of environmental conditions which include climatic data.

The proposed method requires the results of conventional tests such as the grain size analysis, Atterberg limits and the saturated hydraulic conductivity. These results are used for estimating the soil-water characteristic curve (SWCC) using the technique suggested by Catana et al. 2006. In addition, computer modeling studies have to be undertaken using the computer soft-ware such as the SEEP/W, Soilcover and HELP to evaluate the performance of the soil liner. SoilCover is a one-dimensional finite element model useful for predicting the variation of suction, water content and degree of saturation with respect to depth of the soil liner. SEEP/W is two dimensional flow assessment finite element model and HELP software is capable of simulating two dimensional flow behaviors in landfills. The SWCC is an input parameter for the computer software; namely, SEEP/W, SoilCover and HELP.

The proposed approach is useful in evaluating the performance of the soil liner and also verifies whether the proposed guidelines suggested by Ontario Ministry of Environment for the design and construction of liners are satisfactory.

2 BACKGROUND

2.1 Guideline requirements

Several guidelines have been provided by government agencies in Canada and U.S.A. (Fonstad et al, 2001). The guidelines vary from province to province in Canada and various states within the U.S.A. The variations in the suggested guidelines may be attributed to several factors such as the clay properties of the region, environmental factors such as the climate, functionality and the purpose of the liner to be designed and constructed. For example, the Ontario Landfill Standards recommend a hydraulic conductivity of not more than 1 x 10^{-9} m/s for engineered clay liners. Appropriate construction techniques are used in order to achieve the recommended hydraulic conductivity by manipulating the compaction water content, density and compaction energies of the chosen candidate material as soil liner (Benson, 2000).

The hydraulic conductivity of the soil liners used for solid waste disposal landfills is also strongly influenced by environmental factors such as freeze / thaw cycles, which lead to soil cracking and contributes to the formation of channels in the compacted soil, thereby allowing pollutant movement into the natural ground water or aquifer (Benson, 2000 and Bowders et al, 1994). Relatively high temperatures and humidity can also contribute to desiccation cracks which permit the movement of contaminants into the groundwater. Changes in liners due to the environmental factors have been debated by several investigators (Won and Haug 1991, Woon-Hyung and Daniel 1992, Othman and Benson 1993, Bowders and McClelland 1994, Othman et al, 1994, Albretch and Benson, 2001). In order to lessen damages associated with environmental effects on liners, the application of polypropylene fiber reinforcement has been used in soil liner construction to reduce cracks and increase the tensile strength (Miller and Rifai, 2004).

In recent years, soil liners have been routinely used as barriers for waste management structures. However, as discussed in earlier paragraphs, guidelines by regulatory agencies form the key design criteria in the construction of soil liners. To date, there are limited studies undertaken to determine or estimate the soil liner thickness required for the satisfactory performance taking account of factors such as soil properties, hydraulic conductivity behavior under saturated and unsaturated conditions and environmental conditions.

3 TESTING PROGRAM

3.1 Sample Preparation

Two soil samples from the Ottawa region (i.e. Rideau Centre and Aylmer) were used in the present study. The soil sample collected was first air dried and then placed in an oven for removing the natural water content. The sample was then subjected to gentle crushing using rubber mallet to separate the soil particles. Large size soil particles were removed and all the soil was then passed through sieve # 40. The prepared soils were carefully mixed with different water contents and placed in sealed polyethylene bags for a minimum of 3 days period to ensure homogeneous distribution of water content throughout the sample. When the sample achieved equilibrium conditions, the variation of dry unit weight with respect to water content was determined using static compaction stress equal to 100 kPa. Specimen size of 50 mm diameter and 20 mm height were used to develop the relationship between the dry unit weight and water content. Fig. 1 shows the compaction curve for the soil samples undertaken in this study.

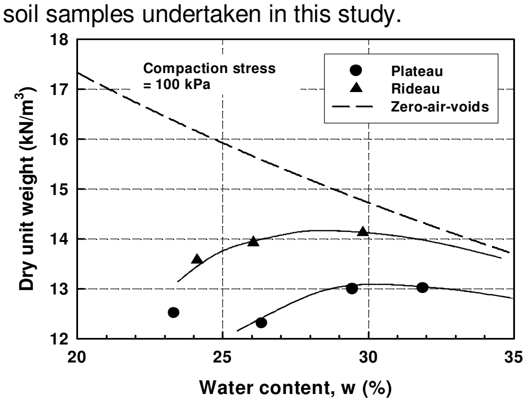


Fig. 1. Compaction Curve for the two candidate materials

Table 1. Physical properties of the soils used in the study.

Properties	Rideau	Plateau
Liquid Limit, w_L (%)	47.6	65.4
Plastic Limit, w_P (%)	22.4	32.8
Plasticity Index, I_p	25.2	32.6
Specific gravity, G_s	2.70	2.73
Max. dry density, γ_d(max) (kN/m^3)	14.2	13.0
Optimum moisture content, OMC (%)	27.6	29.6

The dry density values are relatively low in comparison to other reported dry density versus water content relationships for other Ottawa region clays as the compaction energy used is low. The physical properties of the soils used in the present study are shown in Table 1. Relatively low compaction energy was used intentionally in the present study to study the performance of soil liners compacted to lower density.

3.2 Measurement of Matric Suction

The matric suction of the compacted specimens was measured using modified axis-translation technique. Details of the equipment used and the procedure followed for matric suction measurement are available in Powers et al, 2007. The measured matric suction values for specimens compacted at different water contents using the same static compaction energy of 100 kPa are summarized in Table 2. The results suggest that the matric suction decreases with an increase in the water content. These results are consistent with the results of other investigators (Vanapalli et al, 1999).

Table 2. Matric suction obtained from axis-translation technique.

Rideau		Plateau	
Matric Suction (kPa)	Water Content (%)	Matric Suction (kPa)	Water Content (%)
360	20	340	20
255	22	225	22
147	24	188	24
95	26	115	26
-	-	57	28

3.3 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity values of the compacted soil samples were measured using the Tri-Flex 2 Permeability System following the guidelines from ASTM D 5084 and the US. Army Corps of Engineers, Manual EM 1110-2-1906. The dimensions of the soil specimen were equal to 50 mm in diameter and 100 mm height. The specimens were prepared using a static compaction stress of 100 kPa. The same compaction stress was used for the preparation of all test specimens (i.e., compaction curve, measurement of matric suction in compacted specimens with different water contents, and determination of saturated hydraulic conductivity). Table 3 summarizes the measured hydraulic conductivity values of two soils used in this research program.

Table 3. Saturated hydraulic conductivity of the soils

Soil sample	Saturated hydraulic conductivity (m/s)
Rideau	5.60×10^{-9}
Plateau	9.09×10^{-9}

3.4 Estimation of the soil water characteristic curve (SWCC)

Catana et al, (2006) proposed a relationship between the suction capacity and the product of the liquid limit and the clay fraction based on a regression analysis of 16 fine-grained soils. The suction capacity is defined as the gradient of curve for suctions greater than 100 kPa (*C* – in log kPa / %) (Wardle et al, 1999). This relationship can be used as a tool in the estimation of the SWCC of fine-grained soils. Fig. 2 shows the suction capacity of values of the two soils evaluated in the present study along with the Catana et al, (2006) results. The suction capacity, *C* values of the two soils fall on the best fit regression line.

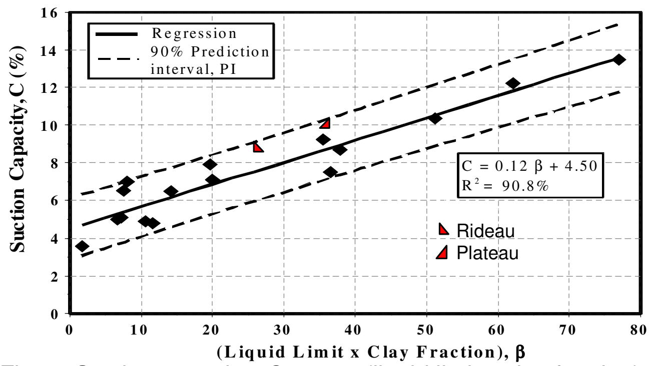


Fig. 2. Suction capacity, *C* versus (liquid limit x clay fraction) [modified] (Catana et al, 2006).

The following procedure was suggested by Catana et al, (2006) used for estimating the SWCC for the two soils studied in the present research program:

- Step 1: The suction capacity, *C* is determined from liquid limit and clay fraction (using Fig. 2)
- Step 2: The suction capacity, *C* and ψ_p are used to estimate the water content at a suction value of 1500 kPa. This value of suction is chosen since most of the compacted fine-grained soils exhibit linear desorption characteristics approximately around 1500 kPa.
- Step 3: One data point of suction versus water content is determined using axis translation technique or any other measurement techniques. In addition to the above information, the saturated water content, w_{sat}, is determined from the volume-mass relationships.

Following the procedure of one point estimation method established by Catana et al, (2006), a SWCC was estimated for the present study as shown in Fig. 3. This figure also shows comparisons between the SWCC measured by Catana et al, (2006) for Champlain Sea Clay with an initial compaction water content of 29.8% and the measured SWCC and the estimated SWCC. Catana et al, (2006) data are in good agreement with the values obtained from Plateau sample. The measured gravimetric water content of Plateau sample was 31.8% and the suction value equal to 57 kPa. As both soils had approximately similar compaction water content and suction relationships (Table 2), it can be inferred that both the soils have approximately the same structure and hence similar SWCC behavior.

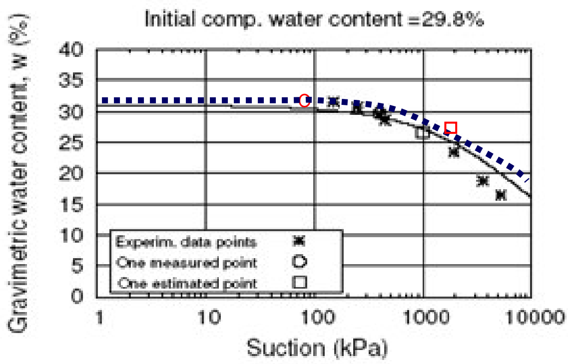


Fig. 3. Estimated soil water characteristic curve for clay sample using the approach presented by Catana et al, 2006.

4 MODELING STUDIES

Modeling studies on the single composite liner were performed by using different finite element software which include SEEP/W, Soil Cover and HELP. The dimensions of the liner were as per the suggested guidelines by the Ontario Ministry of Environment for single composite liners (Fig. 4).

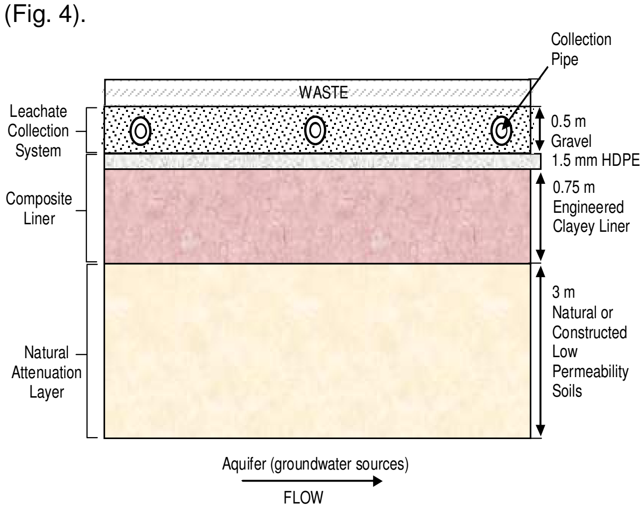


Fig. 4. Single Composite Liner [modified] (Ontario Ministry of Environment, 1998).

4.1 Modeling studies using SoilCover

SoilCover is a finite element modeling software that can be used in the assessment of one-dimensional movement of water in a cover/waste system taking into account infiltration and evapotranspiration (USG, 2000). SoilCover can be used in conjunction with other available flow modeling softwares such as HELP and SEEP/W. The parameters such as freeze/thaw cycles, number of composite liner layers, thickness of each layer, water content or suction, and temperature of each layer were used as input parameters for simulation studies. Climatic information for this modeling was obtained from the Ministry of Environment Weather Office for the Ottawa region. A run of the model for the composite liner zone has shown that the hydraulic conductivity values were lower than 1 x 10^{-9} m/s, which is desirable for the long-term performance of the liner. This is one of the key design criteria required to achieve natural attenuation of several leachate constituents in the composite liner (Bagchi, 1987).

4.2 Modeling studies using SEEP/W

SEEP/W was used in this investigation to simulate the water flow through the composite liner medium. Fig. 5 shows the dimensions of the liner along with the initial boundary conditions at different horizons of the composite liner system following the suggested specifications of the Ontario Landfill Standard, Reg. (232/98) for each layer. The flow is assumed to occur only in the vertical direction. Table 4 shows the values of velocity and hydraulic conductivity at each analyzed level of the liner from simulations.

It can be seen from simulation results that flow velocity through the layers of the single composite liner decreases. Such a behavior can be associated to friction loss and changes in material properties of different layers of the single composite liner. The decreasing flow velocity values in the single composite liner provide assurance to state that contaminant depletion can occur in the soil liner (Bagchi, 1987). Moreover it can be assumed that chemical processes such as dilution-diffusion and adsorption will take place within the system while the contaminants pass through and interact with the soil.

Combined simulations of the horizontal and vertical direction (i.e. X and Y) flow direction using SEEP/W were undertaken to study the variation of the velocity behavior of a single composite liner. The boundary conditions where kept the same for this combination (Fig. 6).

From the two simulations run in SEEP/W it can be seen that through the different layers of the single composite liner, the flow velocity has a decreasing tendency, which as discussed earlier can be attributed to friction loss and possible changes in material properties. For the most part of simulation, flow velocity in the downward movement can be assumed to be equal to the flow velocity in the Y direction. Nevertheless, the combined simulations of flow behavior (i.e. X and Y directions) performance in a soil liner is a more realistic approach; since it takes into account slope differences present in the field and other construction divergences (Table 5).

4.3 Hydrological Evaluation of Landfill Performance (HELP) Model

The Hydrologic Evaluation of Landfill Performance (HELP) computer program is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills (Schroeder et al, 1994). The objective of using HELP is to estimate the annual leachate head and its velocity. The key input parameters required for the execution of the program are: the climate data, soil properties for each liner stratum, and the geomembrane characteristics such as the quality of construction

Table 4. Predicted velocity and conductivity values predicted by SEEP/W in Y direction

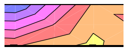
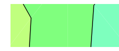
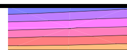
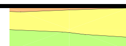
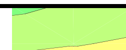
Parameter				
Velocity (m/s)	1.53×10^{-7}	7.38×10^{-9}	9.54×10^{-9}	9.54×10^{-9}
Conductivity (m/s)	1.00×10^{-8}	5.00×10^{-9}	1.00×10^{-9}	1.00×10^{-9}

Table 5. Predicted velocity and conductivity values predicted by SEEP/W in X and Y direction.

Parameter				
Velocity (m/s)	4.58×10^{-7}	8.95×10^{-9}	6.74×10^{-9}	9.83×10^{-9}
Conductivity (m/s)	1.00×10^{-7}	1.00×10^{-11}	1.00×10^{-9}	1.00×10^{-9}

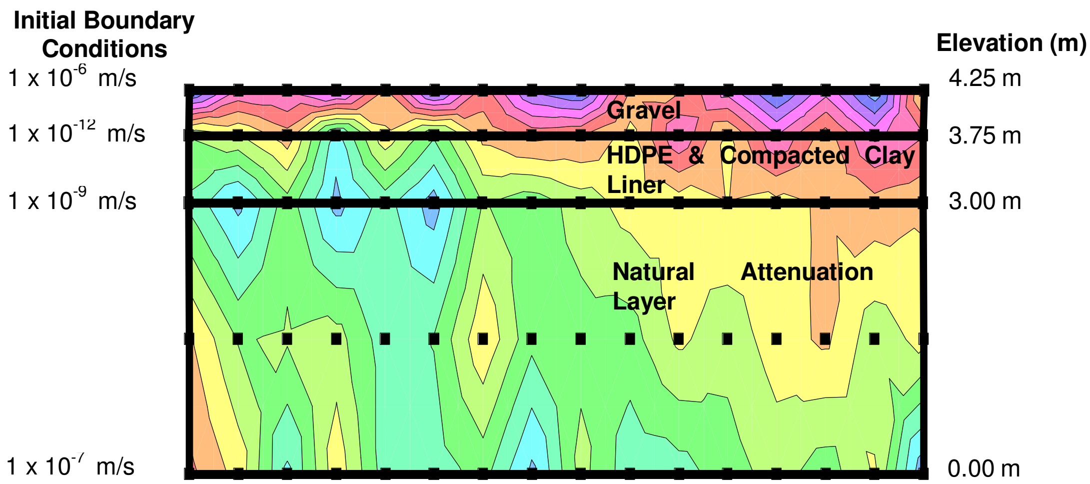


Fig. 5. Flow velocity simulations generated by Seep/W in Y direction .

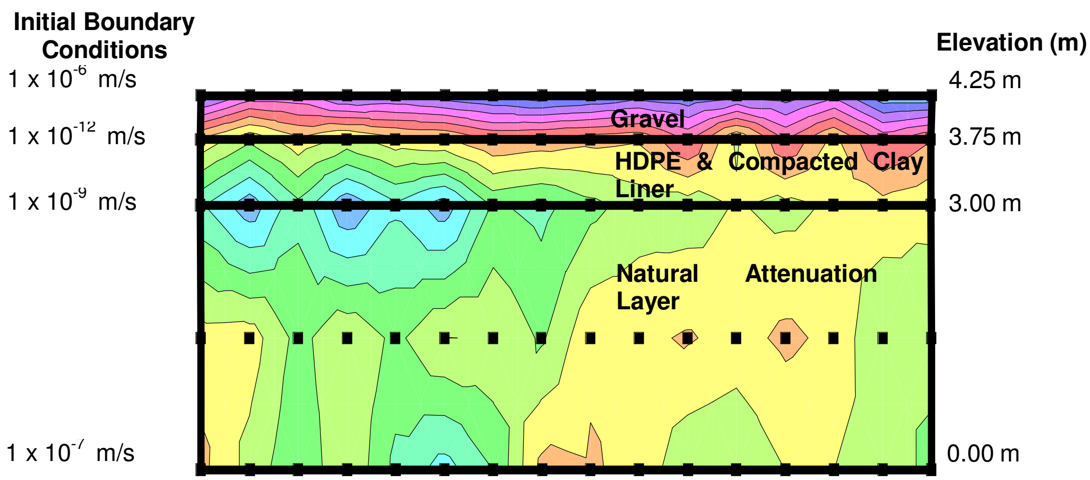


Fig. 6. Flow velocity behavior simulations generated by Seep/W in X and Y direction.

The HELP model provides modeling results for several parameters; however, the most important parameter is the leachate leakage/percolation for the present project. The total leachate head is useful to estimate an appropriate depth based on maximum relative concentration of contaminants. More details on this subject are summarized later (i.e. section 5). The leachate leakage height obtained from this model is equivalent to an annual value of 209.21 mm. This value corresponds to the total leachate amount generated throughout the entire system; disregarding losses or collected leachate from the system.

5 SOIL LINER THICKNESS

The thickness of a compacted clay liner is based on the regulatory guidelines of the region. Fonstad et al, (1999) summarize the guidelines along with the other criteria of followed in various regions in U.S.A and Canada for compacted clay liner construction including the Ontario province guidelines (Table 6). For a new or expanding landfill site in the Ontario province; a compacted clay liner thickness value of 0.75 m is recommended as per the guidelines.

However, the thickness may vary in certain scenarios which include the position of the groundwater level and the type of soil and depth underneath the natural attenuation zone.

Table 6. Summary of design and/or construction practices commonly used in U.S.A and Canada, including Ontario province (modified after Fonstad et al, 1999).

Property	IO	MN	MT	NE	ND	SD	AB	MB	SK	ON*
Acceptable soils (USCS system)	CL, CH, SC, GC	CL, CH, SC, GC				CL or CH				**CL or CH**
Clay (%)	>20	>20				>30	>20	>20	>10	**>20%**
Plasticity Index (%)	10 – 25	10 – 25			>15	>15			>10	**11 - 30**
Standard Proctor Energy (%)	>95	>95	>95	>95	>95	>95	>95	>95	>95	**>95**
Water content (% of optimum)	0 to +4	0 to +4	0 to +4					-1.5 to +4	0 to +4	**Slightly wet of optimum**
Hydraulic conductivity (cm/sec)	1.8×10^{-6}	5.2×10^{-7}	4.6×10^{-7}	7.3×10^{-6}	3.7×10^{-6}	1.8×10^{-6}	10^{-7}	10^{-7}	10^{-7}	$\mathbf{10^{-7}}$
Minimum liner thickness (m)	0.3	0.6	0.15	0.6	0.3	0.45	0.6	0.6	0.15	**0.75**
Most common liner thickness (m)	0.6	0.9	0.3	0.9	0.6	0.75		0.6+	0.6	**0.75+**

Note: IO = Iowa, MN = Minnesota, MT = Montana, NE = Nebraska, ND = North Dakota, SD = South Dakota, AB = Alberta, MB = Manitoba, SK = Saskatchewan, ON* = Ontario (Present study compilation)
Notes:
Clay (%): Ontario Ministry of Agriculture, Food & Rural affaires (2002)
Plasticity Index, Standard Proctor Energy: Ontario Ministry of Agriculture, Food & Rural affaires (2002)
Hydraulic Conductivity & Minimum thickness (Ontario Ministry of Environment, Ontario Regulation 232/98; Environmental Protection Act)
Common thickness: 1.2 m (Quigley et al, 1988);1 m (Ontario Ministry of Agriculture, Food & Rural affaires (2002)

Table 7. Leachate characteristics (Ontario Landfill Standard, Reg. 232/98).

Contaminant	Initial Source Concentration (mg/L)	Mass as Proportion of Total (wet) Mass of Waste (mg/kg)	Half-Life in Leachate (years)	Health Related Drinking Water Objective (mg/L)	Aesthetic Drinking Water Objective (mg/L)
1. Benzene	0.02	0.0014	25	0.005	n/a
2. Cadmium	0.05	0.035	n/a	0.005	n/a
3. Chloride[1] 150,000 t/ha increasing to 250,000 t/ha	1,500 increasing to 2500	1,800	n/a	n/a	250
4. Lead	0.6	0.42	n/a	0.01	n/a
5. 1,4 Dichloro-benzene	0.01	0.007	50	n/a	0.001
6. Dicholor-methane	3.3	2.3	10	0.05	n/a
7. Toluene	1	0.7	15	n/a	0.024
8. Vinyl Chloride	0.05	0.039	25	0.002	n/a

The moisture content and the degree of saturation influence the contaminant depletion process throughout the composite liner system. One of the objectives of the liner system is to ensure that the contaminant concentration is at reduced levels. Therefore, it is important to estimate the appropriate thickness required for the liner system. Darcy's velocity is a parameter that helps to define the necessary depth in a soil liner in order to allow the natural attenuation process for the contaminants. Darcy's velocity in municipal landfill has been found to be in the range of 0.003 to 0.03 m/yr, according to Mathur and Jayawardena (2008). Mathur and Jayawardena (2008) have provided several design charts to estimate the thickness of liners based on the maximum concentration of the solute and the Darcy's velocity. Other guidelines for leachate characteristics are also available according to the Ontario Landfill Standards, Reg. 232/98 are shown in Table 7.

Health related drinking water contaminant concentration is another key parameter in water and/or waste management engineering projects. A satisfactory depth of a liner should be provided to allow depletion of contaminant concentration in accordance with the environmental guidelines. The maximum contaminant concentration for health related drinking water contaminant concentration should not exceed a value of 0.072 mg/L as per Ontario Landfill Standards (Reg. 232/98). An approximate leachate head, H_f has been estimated from HELP modeling as 0.2 m (i.e. more exactly, 209.21 mm) to satisfy this criterion. The above data was used in combination with Fig. 7 in order to estimate the compacted clay liner thickness.

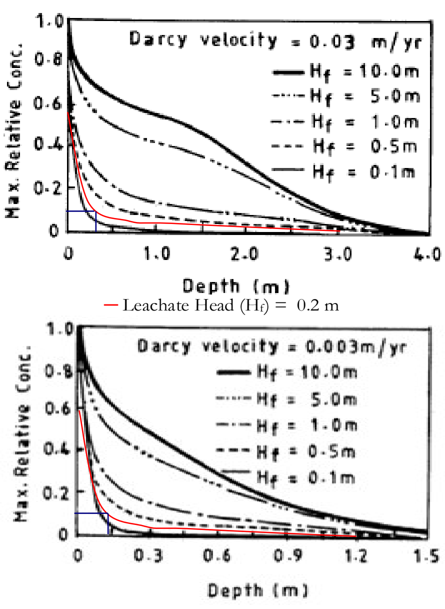


Fig. 7. Spatial variation of maximum relative concentration [modified] (Mathur and Jayawardena, 2008).

The velocity in the 3 m depth of the natural attenuation layer is in the order of 10^{-8} to 10^{-9} m/s (see Fig. 7). It can be observed that for a Darcy velocity of 0.03 m/yr, a depth of approximately 0.4 m is obtained; whereas for velocity of 0.003 m/yr, a 0.15 m is sufficient. The results suggest that a reduction in the compacted clay liner thickness is possible without compromising with the groundwater safety.

6 SUMMARY AND CONCLUSIONS

The suitability of two fine-grained clayey soils from the National Capital Region (Ottawa-Gatineau) was studied for their suitability as candidate materials for soil liners in waste containment structures. The suitability of both these soils was based on the guidelines proposed by various regulatory agencies from Canada and USA. The regulatory agencies suggest that the candidate materials proposed for use as soil liners should satisfy criteria based on Atterberg limits, percentage of clay, density at standard compaction energy and saturated hydraulic conductivity. In addition, these agencies have provided recommendations with respect to minimum thickness for the compacted liners that can be used for waste management structures for their satisfactory performance (USAEPA (1990), USAEPA (2004), Ontario Landfill Standards, Reg. 232/98).

A different approach is presented through the study presented in this paper to provide a rational basis for estimating the thickness of the compacted soil liners for waste management structures. This approach is based on both the mechanics of saturated and unsaturated soils taking account of environmental conditions which include climatic data. Experimental studies, empirical relationships and computer modeling are required for estimating the soil liner thickness using the approach presented and tested in this paper. The experimental studies include conventional tests, empirical procedures based on simple established relationships, and modeling studies that use computer soft-ware such as SEEP/W, Soilcover and HELP.

The study shows that the presently suggested guidelines are valuable for the design of soil liners. Modeling studies from the present research show that there is feasibility of a reduction in the compacted clay thickness of the composite liner from recommended value of 0.75 m. Furthermore, surveillance and monitoring regulations of the unsaturated/vadose zone is recommended to be included in future within the existent Ontario Landfill Standards (Reg. 232/98) for the appropriate design and long term use of composite liner, ensuring its good performance and life service.

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