MOISTURE FLOW THROUGH MUNICIPAL SOLID WASTE: PATTERNS AND CHARACTERISTICS*

CHRIS ZEISS, PH.D.

WADE MAJOR, B.SC.

University of Alberta
Edmonton

ABSTRACT

Vertical moisture flow through compacted municipal waste layers is more complex than the one-dimensional, uniform Darcian drainage flow through a constant homogeneous medium as modeled in HELP. Channeling and flow along wetting curves produce irregular and more rapid breakthrough times and leakage rates. Tests of compacted municipal waste show distinct channeled flow in two to three streams in cylindrical cells. Furthermore, practical field capacity is substantially lower at 0.136 than the HELP default value of 0.292. Porosity, while similar to the default value of 0.52, varies with compaction ratio from 0.58 to 0.47. As a result, practical unsaturated hydraulic conductivities are 10^4 to 10^5 higher at $1.2 \cdot 10^{-3}$ to $1.7 \cdot 10^{-2}$ cm/s than the HELP default of $1.2 \cdot 10^{-7}$ cm/s. As a result, waste default values should be revised in current models, while new leachate generation models need to account for channeled flow.

PROBLEM STATEMENT

The determination of velocity and discharge rate of water through layers of municipal waste is crucial for the prediction of the time of first discharge and the quantity of leachate flows from municipal waste landfills. These values are used to design leachate collection systems and to predict the maximum quantities of leachate percolating through the liner systems with water balance methods such as the Hydrologic Evaluation of Landfill Performance (HELP) model [1].

The HELP model assumes a one dimensional Darcian unsaturated drainage flow from a homogeneous medium with constant characteristics over time. The moisture moves vertically downwards as a horizontal front driven by the vertical hydraulic gradient of unity. Field capacity, porosity, capillary pressures and pore size distributions are used to correct the saturated hydraulic conductivity for unsaturated conditions by applying combined Campbell [2] and Brooks Corey [3] equations. Observations of actual leachate movement in wastes [4-7], however, note channeling effects. Channeling is the vertical flow of liquid through channels with cross sectional areas which are substantially less than the cross section of the top layer of waste where infiltration occurs. The constriction of flow into channels through the waste layers in landfills is predicted to significantly reduce breakthrough and flow time from infiltration into the top waste surface until discharge to the underlying drainage layer. Furthermore, the practical field capacity for channeled flow, a measure of the moisture storage capacity of the waste layer, and the wilting point, the minimum moisture content at which plants can survive in soil-like materials, are expected to be substantially smaller than previously measured for Darcian drainage flow. The resulting unsaturated and saturated hydraulic conductivities are predicted to be substantially higher for practical channeled flow than previously measured for non-channeled flow-through waste. The observation of significant channeling would furthermore indicate the need for a revision or extension of the Darcian flow model for municipal wastes.

Compacted waste layers consist of very large particles with large pore spaces between them. These objects contain smaller particles and pore spaces enclosed within the outer envelope (garbage bags, etc.). Finally, small particles contain pore spaces within. While Darcian flow assumes homogeneous particle sizes and pore volumes, channeled flow predicts that the large, interconnected pore volumes between large particles and objects will lead to preferred flow channels which transport the bulk of water rapidly. The smaller pores between and within particles are likely, at least initially, to contribute less to the flow. If channeling increases flow velocity and conductivity, then revised models should include the constricted and rapid flow through narrow channels formed by large pores in addition to the slower advance of the moisture front through combined Darcian flow and capillary action in smaller pores.

THEORY OF VERTICAL FLOW THROUGH MUNICIPAL WASTE LAYERS

HELP Model

In the HELP model moisture movement through the waste layer is predicted as Darcian flow through a homogeneous, unsaturated porous medium with constant porosity, pore size distribution, bubbling pressure and residual saturation [1]. Darcian flow requires that the flow be laminar and uniform. The flow is furthermore treated as one dimensional with a vertical hydraulic gradient of unity. As a consequence of these assumptions, estimates for flow velocity and breakthrough time are determined with the following relationships as functions of the unsaturated hydraulic conductivity and the waste porosity (see variable definitions in the Notation list):

$$\bar{v} = \frac{K_{us}\frac{dh}{d}}{n} = \frac{h}{t_{bt}} \tag{1}$$

$$K_{us} = \frac{h}{t_{bt}} \cdot \frac{n}{\frac{dh}{d}} = \frac{h \cdot n}{t_{bt} \cdot 1} \tag{2}$$

Another way of calculating unsaturated hydraulic conductivity is through measurement of discharge rate Q_{lk}:

$$Q_{lk} = q \cdot A = K_{us}\frac{dh}{d} \cdot A \tag{3}$$

$$K_{us} = \frac{Q}{A \cdot \frac{dh}{d}} = \frac{Q}{A \cdot 1} \tag{4}$$

The unsaturated hydraulic conductivity varies with the soil moisture content. The adjustment of the unsaturated hydraulic conductivity is accomplished through the application of the combined Brooks-Corey and Campbell equations to values for solid waste characteristics.

The Brooks-Corey equations were developed to model the drainage behavior of two phase air-fluid flows through unsaturated porous media [3]. The relationship models the interactions of liquid and gas flows to establish a relationship between capillary pressure and effective saturation as a function of the pore size distribution λ. HELP uses this equation with the effective saturation determined from soil moisture content, SM, residual soil moisture content RS, and porosity n as follows (see Notation list):

$$\left[\frac{SM - RS}{n - RS}\right] = \left[\frac{\Psi_b}{\Psi}\right]^\lambda \tag{5}$$

With known residual soil moisture content, porosity and bubbling pressure and with measurements of two sets of soil moisture content and corresponding capillary pressure, (field capacity FC at 0.3 atm and wilting point WP at 15 atm in HELP), the data can be plotted as a straight line on a log-log graph of the effective saturation (left hand side of equation 5) and capillary pressure (right hand side of equation 5). The absolute value of the slope is the pore size distribution index λ with the bubbling pressure ψ_b as the intercept with capillary pressure at effective saturation of unity.

Because moisture infiltrates into the waste layer from overlying final or daily cover layers, the resulting soil moisture content is updated in a six hour time step in the HELP program to predict the resulting hydraulic conductivity for the next time step. The pore size distribution index is then used in the Campbell equation in conjunction with the effective saturation (left hand side of equation 5) to determine the correction factor to be multiplied with the saturated hydraulic conductivity to determine the unsaturated hydraulic conductivity at the actual soil moisture content:

$$K_{us} = K_s \cdot \left[\frac{SM - RS}{n - RS}\right]^{3 + \frac{2}{\lambda}} \tag{6}$$

Key variables in the prediction of unsaturated flows through the waste layers are therefore (in the order of required use):

1. Soil moisture content SM evaluated at field capacity, FC, and at wilting point, WP
2. Porosity n
3. Residual soil moisture content RS
4. Bubbling pressure ψ_b
5. Suction head (capillary pressure) ψ
6. Pore size distribution index λ, and
7. Saturated hydraulic conductivity K

In HELP, values for municipal solid waste are provided from measurements or from derivations of similar soil media. These values will be discussed below in order to predict the practically observed values under channeled flow conditions. Principal differences and predicted practical values for the seven variables are discussed.

Channeled Flow Through Municipal Solid Waste

Municipal solid waste consists of a heterogeneous mix of materials, particle sizes and moisture contents. Median particle sizes of opened municipal waste are

reported to be at or above four to six inches [8]. If the particle sizes of objects in the raw waste stream were to be considered as they are placed in landfills, then garbage bags, furniture, lumber, appliances, and other large objects would most likely result in a much larger median particle size. While compaction by heavy equipment, cover and overburden partially open, flatten and orient the objects in the horizontal direction, large pore spaces still occur and large objects still act as interceptors of horizontal flows and as vertical flow channels. Channeling, the preferred flow of moisture through narrow flow pathways, has been mentioned [4, 6, 9] and observed in shredded waste [7] and in two phase flow through unsaturated soils [10]. Given the large pore volumes and intercepting objects in the waste, preferred flow channels are expected to develop and to result in rapid vertical percolation confined to narrow flow channels in the waste layer.

Because the waste is placed with a moisture content of 20 to 30 percent, infiltrating water must wet and build up moisture content to the point where downward flow occurs [11]. The moisture content at which free drainage, beginning from saturation and following the drainage curve, just stops, is the field capacity, FC_H [13]. HELP uses field capacity values of 0.294, while Bagchi cites measured values of 0.12 to 0.137 [4]. Channeling will result in a much lower practical field capacity for waste because only the surface area surrounding the channels is wetted as opposed to the complete surface area of all interconnected pores as measured with the HELP definition of field capacity. Furthermore, the waste moisture content is expected to be lower for flow during the wetting cycle than during drainage. Thus, the practical field capacity of municipal waste is expected to be lower than the value used in HELP model (see Table 1).

Table 1. Default Waste and Flow Characteristics for Municipal Waste Layer in HELP

Municipal Waste Characteristics	Field Capacity FC $\left[\dfrac{Vol}{Vol}\right]$ at 0.3 atm. on drainage curve = 0.294	Wilting Point WP $\left[\dfrac{Vol}{Vol}\right]$ at 15 atm on drainage curve = 0.140	Porosity n $\left[\dfrac{Vol}{Vol}\right]$ = 0.52	Soil Moisture Content at Residual Saturation RS $\left[\dfrac{Vol}{Vol}\right]$ = 0.015
Municipal Waste Flow Characteristics	Bubbling Pressure Ψ_b [cm]	Pore Size Distribution Index λ	Saturated Hydraulic Conductivity K [cm/s]	Unsaturated Hydraulic Conductivity (at FC) K_{us} [cm/s]
	20.76	0.211	$2.0 \cdot 10^{-4}$	$1.2 \cdot 10^{-7}$

Porosity for waste was measured to obtain the default value of 0.52 as used in the HELP model. There is no apparent reason to predict different porosities. However, porosity and the alignment of pores are expected to decrease as the result of waste compaction, settlement, and biodegradation in the landfill. While the HELP model assumes porosity to be a constant, it is obvious that the pore volume and alignment will change as particles compress and degrade. Porosity is predicted to decrease with higher compaction and with time due to settlement and biodegradation, resulting in higher field capacities and hydraulic conductivities.

The soil moisture content is estimated as the vertical asymptote on the effective saturation versus capillary pressure curve. A second estimate is obtained by fitting the value from the first estimate to the straight line on the log effective saturation versus log of suction head, the same line for which the slope equals the pore size distribution index [3]. The HELP value for residual soil moisture content of 0.015 was obtained from experimental data extracted from Rawls et al. [12]. Since this value is identical for drainage and wetting cycles, there is no reason to expect significant differences. Because of the large dead volumes (in bags and containers) that absorb and collect moisture, but do not act as channels, the ineffective residual moisture content within waste particles is expected to be high. However, for the active flow area the HELP value will be adopted here.

Bubbling pressure ψ_b is the capillary pressure at which the water saturation first drops below unity. The bubbling pressure is higher than zero suction head because the tension saturation keeps the pores saturated (see Figure 1). Bubbling pressure is determined from the log of effective saturation versus log of capillary pressure line at the point where the extension of the straight line section intercepts the effective saturation value of 1.0. On the wetting cycle, tension saturation should be reached at a lower pressure [13] (see Figure 1). Furthermore, because of large interparticle pore spaces in channeled wetting flow, it is expected that the resulting bubbling pressure will be lower (in absolute value) than the drainage bubbling pressure.

The capillary pressure (suction head) is set or measured in relation to corresponding effective saturation values. Field capacity saturation corresponds with 0.3 atm capillary pressure head wilting point with 15 atm to provide two points on the curve. In contrast to the drainage curve used in HELP, channeling behavior in the wetting cycle is predicted to produce lower values of effective saturation at corresponding capillary pressures. In order to construct the wetting log effective saturation-log capillary pressure head curve, another point on the straight line portion of the curve must be identified. Since the determination of wilting point with a 600 g sample is impractical for municipal solid waste, two alternate estimates for a point on the lower portion of the curve are applied. First, air dried moisture content of the waste was measured and set to correspond with capillary pressure head of 3,000 to 5,000 kPa in air dried waste [9]. Then, corresponding values of water content and suction head were obtained from measurements in two municipal wastes landfills [9]. Air dried waste showed capillary pressures of
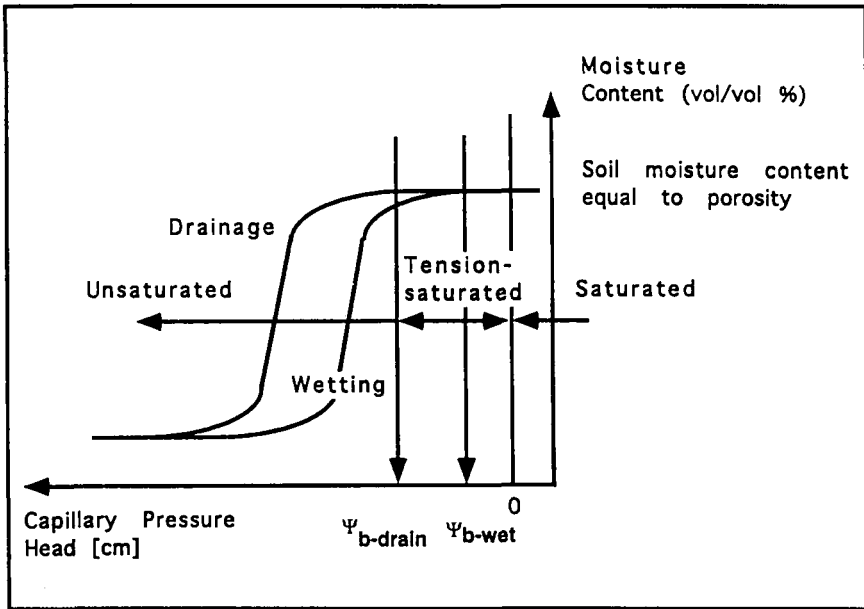
Figure 1. Characteristic curves for drainage and wetting cycles.

5,300 kPa and 3,050 kPa in the surface layers with corresponding moisture contents of 0.03 and 0.06 respectively. These values are plotted and checked for consistency.

Saturated values of hydraulic conductivity are found in the literature to exhibit large variation from 10^{-1} to 10^{-5} cm/s [14, 15]. Version 2 of HELP uses $2.0 \cdot 10^{-4}$ cm/s. Channeling effects are expected to result in shorter breakthrough times and high discharges. Backcalculating the effective unsaturated hydraulic conductivity using the entire waste cross sectional area will result in higher effective hydraulic conductivity K_{us}'. The prime symbols are added to denote that these are not strictly Darcian hydraulic conductivities, but rather that they are effective conductivities calculated as though Darcian flow were occurring, but realizing that channeled flow occurs. The results allow a comparison of the actual flow velocities and discharges with Darcian values in order to estimate discrepancies.

EXPERIMENTAL MEASUREMENTS AND ANALYSIS

The purpose of the experiments was to measure in landfilled municipal waste the patterns of moisture flow and those key variables that were expected to be affected by flow channeling and waste compaction. Practical field capacity FC', theoretical field capacity FC_H, porosity n, density ρw, breakthrough time t_{bt}, and

leakage discharge rate Q values were obtained for three compaction ratios of 1.6, 1.67 and 2.85 to determine the effect of compaction.

Measurement Methods

Three sets of three moisture movement tests each were conducted with municipal waste in designed landfill simulator cells. Each cell consisted of two, fifty-five-gallon drums welded together to form a 1.8 m high cylinder with a diameter of 0.57 m. The cells were equipped with sloping bottoms and discharge valves. The cells were filled, from bottom to top, with 1) 7.5 cm (3 inches) layer of drain soil, 2) the waste layer with three moisture flow sensor plates at 1/6, 1/2 and 5/6 of the waste column height, 3) 7.5 cm (3 inches) of soil cover and 4) for the two higher compaction ratios, one or four perforated pressure plates of 100 kg each to simulate equipment and overburden compaction (see Figure 2). For the high compaction ratio tests, four pressure plates compressed the waste column to about 0.7 m height so only one flow sensor plate could be placed at 0.35 m height in these tests. Flow sensor plates consisted of a circular frame with a wire grid holding 20 1.5 cm diameter, 1.5 cm high cups on square 12 cm centres (see Figure 3). Two wires run into each of the cups so that they are separated by a small distance. As leachate flows through the wastewater and over the sensor plates certain cups will fill with leachate causing a complete circuit to be formed. When a circuit is made, a light emitting diode wired to the external control panel corresponding to the cup in the leachate flow will turn on. The flow sensor lights were tested before and after each test to verify complete function.

Nine waste loads of approximately 50 kg each were obtained from residential waste loads at the West Edmonton landfill. Each load was opened so larger particles and objects were between one-fifth to one-tenth the diameter of the cell (0.57 m). This range of size ratios reduces channeling by exposing to the moisture smaller particles than in the raw waste stream. Normally these smaller particles are contained in larger bags or as larger objects. Therefore, the particle sizes are expected to bias flow patterns against channeling. Initial and air dried soil moisture contents were measured by first measuring moisture loss by surface air drying for twenty-four hours, followed by surface oven drying for one hour at 60°C. At this point the surfaces of waste particles were completely dry, except where they were in close contact with adjacent particles. Thereafter, waste particles were further opened and dried for twenty-four hours to obtain the ineffective (within particle) residual moisture content. Particle size distributions were determined by screening 3 to 5 kg samples and calculating of Rosin-Rammler characteristic particle sizes (x_o) and curve slopes (Rosin-Rammler n).

After loading and compacting the waste, moisture was applied either directly to the cover layer or through the perforated pressure plates at a moisture loading rate of 2 L every five minutes, equivalent to an infiltration rate of 94.6 mm/hr. This is equivalent to high rainfall intensity usually lasting less than thirty minutes for five
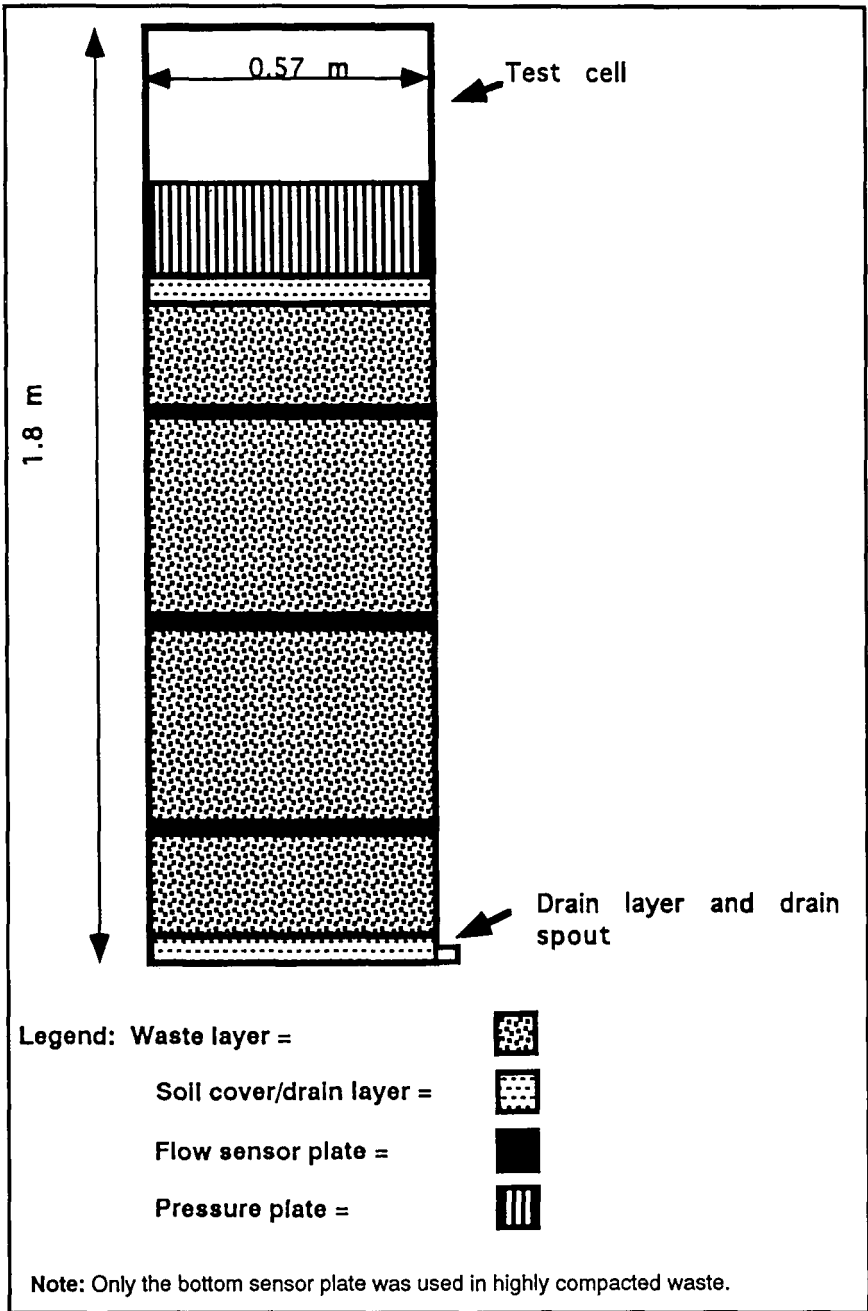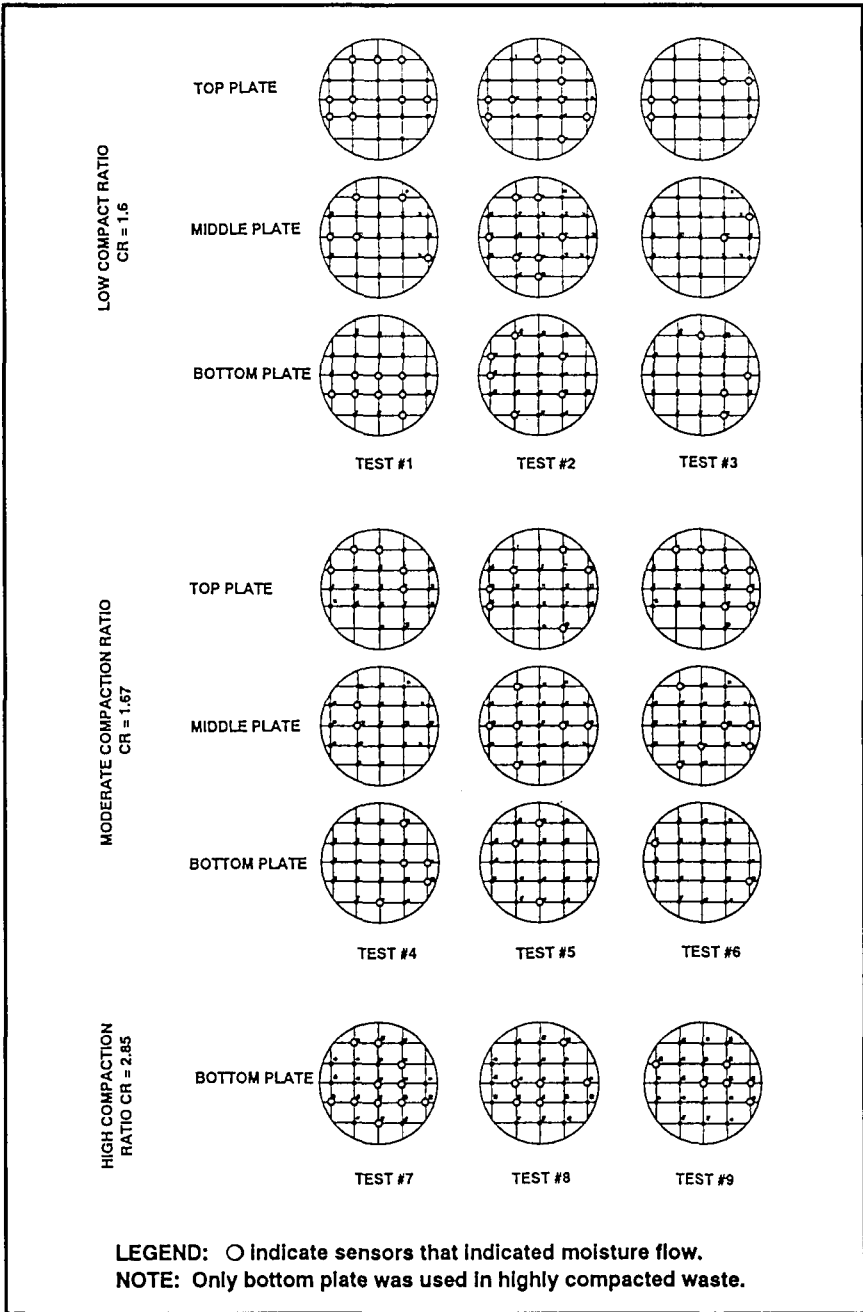
Figure 2. Landfill test cell design.

Figure 3. Measured flow patterns in municipal waste.

to thirty year storm events [16]. The simulated infiltration rate is applicable to high intensity storm events.

After each application, flow indicator lights and the leakage valve were monitored; breakthrough time was determined and thereafter leakage volume was measured simultaneously with moisture application. The test was continued until the increase in leakage discharge reached a steadily increasing rate, at least thirty minutes after initial breakthrough. The added volume of water less total drained volume was calculated as the practical field capacity FC'. After complete free drainage, the outlet was sealed and water was added until saturation of the waste column was reached. Water was again freely drained overnight. The total volume of added water represented waste porosity n while the difference between added and drained water constituted the theoretical field capacity as measured for HELP FV_H.

Analysis Methods

Particle sizes and Rosin-Rammler curve slopes were averaged for all nine samples and the mean was compared with literature values for raw municipal waste to demonstrate smaller particle sizes with comparable distribution slopes. Moisture contents, too, were averaged and standard errors were estimated. The characteristics of the waste column and their effects on flow patterns were tested by difference of means tests of density, porosity and field capacities and by one-way analyses of variance between subsets of three cells by low, moderate and high compaction ratios. Differences of means of practical and HELP field capacities were used to test for significant differences caused by channeling. Finally, correlations of field capacities and unsaturated hydraulic conductivities with density and porosity values were estimated with Pearson linear correlation and Spearman's Rho (non-parametric) rank order correlation coefficients to test for predictive association. The derived variables, unsaturated hydraulic conductivity, bubbling pressure and pore size distribution index, were calculated or graphically determined and compared with the HELP default values. Hydraulic conductivity values were tested with paired differences of means tests. Statistical results were considered significant if the statistic probabilities were equal or less than 0.05, equivalent to a 95% range of confidence.

RESULTS

Waste Material

Characteristic particle sizes among nine samples averaged 9.05 cm (3.5 inches) with a 95 percent confidence interval of 2.9 to 15.3 cm (1.2 to 6.0 inches, see Table 2). This is within the bounds of reported values for raw waste of 8.9 to 17.8 cm and slightly above the values for shredded waste (average $X_o = 6.4$ cm)

Table 2. Waste Particle Sizes and Moisture Contents

Sample No.	Characteristic Particle Size X_0 [cm]	Rosin-Rammler Distribution Slope n	Initial Moisture Content $\left[\dfrac{Vol}{Vol}\right]$	Air Dried Moisture Content $\left[\dfrac{Vol}{Vol}\right]$
1	5.5	1.55	0.05	0.0115
2	3.9	1.14	0.034	0.0096
3	5.9	1.09	0.039	0.0160
4	33.7	0.91	0.024	0.0100
5	5.1	1.63	0.027	0.0084
6	7.4	1.32	0.058	0.0160
7	3.5	0.93	0.032	0.0170
8	6.0	0.62	0.024	0.0151
9	10.5	0.74	0.018	0.0120
Mean	9.05 cm	1.10	0.034	0.0128
Std. Error $n = 9$	3.14 cm	0.09	0.0042	0.0011

[8]. Rosin-Rammler particle size distribution slopes average 1.1 with a confidence interval from 0.87 to 1.33. These values are similar to published values for raw waste (Rosin-Rammler $n = 1.17$ to 1.33) [8], but higher than the values for shredded waste ($n = 0.79$). Smaller particle sizes and distribution slopes indicate smaller average particle sizes. As a result, the waste characteristics are consistent with reported values. Unopened raw waste is likely to consist of larger particles; the tested samples will generate a more homogeneous flow pattern than unopened raw waste due to their smaller average particle size.

Particle sizes in the nine samples showed some association with type of material. Paper, cardboard, and plastic make up larger sizes above 100 mm (or 4 inches), organics, cans and foodwaste are found mainly in the mid-range (25 to 50 mm, or 1 to 2 inches); and grass, small organics, sand, dirt and small plastics, fall into the pan (below 25 mm or 1 inch size).

Initial (external) moisture contents of the samples averaged 0.034 with a standard error of 0.0042 (see Table 2). This value is consistent with the initial moisture content range of 0.021 to 0.067 reported in Bagchi for municipal solid waste [4]. The average external initial moisture content was added to the moisture volume measured to reach field capacity (see below). Air dried moisture content averaged 0.0128 with a standard error of 0.0011. Finally, ineffective (internal) residual moisture contents averaged 0.06. None of the average moisture contents differed significantly between waste compaction groups.

Moisture Flow and Waste Column

Flow channeling was measured by FlCh, the fraction of the cross sectional area through which moisture movement was observed. An areal fraction significantly less than unity combined with flow patterns consisting of unconnected areas of preferred flow indicate channeling and contradict vertical one-dimensional Darcian flow. Figure 3 and Table 3 present the recorded flow patterns and the results for the fraction of area with active flow as averages of three cells in low, moderate and highly compacted cells. For all three sensor plate heights in the waste columns, the areas of flow are significantly less than unity at 34.2 percent, 23.3 percent, and 28.3 percent for upper, middle and lowest sensor plates respectively. While upper and middle flow area means differ significantly, the observed flow areas do not vary significantly by compaction ratio. (ANOVA F ratios from 0.00 to 2.93, probability from 1.0 to 0.13). By observation of Figure 3, two to three clusters of adjacent, lit detectors indicate connected flow channels. Most of the flow areas are unconnected, that is, separated by at least one sensor unit. These results suggest channeled flow patterns through waste.

Waste column density, field capacities and porosity are presented in Table 3 as means and standard errors by compaction ratio. The densities of low (mean = 165.6 kg/m^3) and moderately compacted (186.7 kg/m^3) cells do not differ significantly, but their combined values are significantly lower than highly compacted cells' mean density of 304.5 kg/m^3. The density also shows significant association with compaction ratio (ANOVA F prob. < 0.0001), as expected. The highest achieved density was 327.8 kg/m^3, within the range of reported waste densities [15]. Porosity mean values range from 0.582 for low, to 0.532 for moderate and 0.474 for high compaction cells. Similar to density, the value for moderate compaction does not differ significantly from low and high compaction values, but low and combined low and moderate values are significantly higher than high compaction values. Analysis of variance indicates significant association of porosity with compaction ratio (F prob. = 0.015). Practical field capacity means range from 0.123 for low to 0.141 for moderate, to 0.143 for high compaction cells (see Table 3). Although slightly increased for higher compaction, the means do not significantly vary with compaction ratio. The measured values also do not differ from the range of 0.12 to 0.137 summarized in Bagchi [4]. HELP field capacities increase with compaction ratio from 0.256 for low, to 0.274 for moderate to 0.366 for high compaction and bracket the HELP default value of 0.292. Moreover low and moderate compaction means do not differ significantly, but combined, are significantly less than the high compaction cell mean ($p = 0.05$). The ANOVA test indicates significant association with compaction ratio (F ratio = 12.6, prob. = 0.007). The mean practical field capacity of all cells (0.136) is significantly less than the measured HELP field capacity of 0.299 and less than the HELP default value of 0.292. These results are consistent with

Table 3. Waste Column and Moisture Flow Results

Compaction		Compaction Ratio CR [Vol/Vol]	Density ρ_w [kg/m³]	Porosity n [Vol voids/Vol total]	Flow Channel Area FICh (fraction)			Field Capacity Practical FC'	Field Capacity HELP FC_H
Low (Cells 1,2,3) $n=3$	Mean	1.6	165.6	0.582	Level 1:	Ø	0.38	0.123	0.256
	Std. Error		23.9	0.022		SE	0.067	0.007	0.013
					Level 2:	Ø	0.23		
						SE	0.073		
					Level 3:	Ø	0.30		
						SE	0.058		
Moderate (Cells 4,5,6) $n=3$	Mean	1.67	186.7	0.532	Level 1:	Ø	0.0	0.141	0.274
	Std. Error		4.9	0.035		SE	0.029	0.007	0.005
					Level 2:	Ø	0.23		
						SE	0.067		
					Level 3:	Ø	0.17		
						SE	0.044		
High (Cells 7,8,9) $n=3$	Mean	2.85	304.5	0.474	Level 1:	Ø	n.a.	0.143	0.366
	Std. Error		13.3	0.015				0.024	0.025
					Level 2:	Ø	n.a.		
					Level 3:	Ø	0.38		
						SE	0.04		
Overall Means		2.04	218.9	0.53	Level 1:	Ø	0.34	0.136	0.299
	Std. Error	0.03	9.3	0.015		SE	0.03	0.009	0.01
					Level 2:	Ø	0.23		
						SE	0.04		
					Level 3:	Ø	0.28		
						SE	0.04		

the observed channeling and with the predicted reduced practical field capacity for channeled flow.

Finally, field capacities were tested for correlation with density and porosity. Practical field capacities FC' varied little by compaction. As expected FC' showed no association with density ($p = 0.576$) or porosity ($p = 0.174$). HELP field capacity FH_H significantly correlated with both waste density (Pearson's coefficient = 0.83, $p = 0.005$ and Spearman's Rho = 0.91, $p = 0.001$) and porosity (Pearson's coefficient = 0.67, Spearman's Rho = –0.59, $p < 0.05$).

Apparent hydraulic conductivities in the waste cells were calculated, first, as K_{us} (initial) with equation 2, measured breakthrough time t_{bt} and porosity n, and, second, as K_{us}' (ultimate) with equation 4 and the measured discharge rate Q_{lk}. These values are calculated with Darcian equations although the flow patterns are channeled. Table 4 provides the means and standard errors for K_{us}' (initial) and K_{us}' (ultimate). Average flow velocities ranged from 0.0365 cm/s for low to 0.0280 cm/s for high compaction, with an overall average of 0.0323 cm/s. The variation by compaction ratio is non-significant (ANOVA $F = 0.95$, $p = 0.44$). Downward flow velocity does not decrease significantly with compaction,

Table 4. Flow Velocity, Discharge Rate and Apparent Hydraulic Conductivities — Results

Compaction		Average Flow Velocity $\bar{v}$ $\left[\dfrac{cm}{s}\right]$	K_{us}' Initial $\left[\dfrac{cm}{s}\right]$	Drainage Rate Q_{lk} $\left[\dfrac{L}{5\,min}\right]$	K_{us}' Ultimate $\left[\dfrac{cm}{s}\right]$
Low	Mean	0.0365	0.0214	0.85	$1.12 \cdot 10^{-3}$
(Cells 1,2,3)	S.E.	0.0013	0.0012	0.14	$1.9 \cdot 10^{-4}$
$n = 3$					
Moderate	Mean	0.0324	0.0175	1.03	$1.35 \cdot 10^{-3}$
(Cells 4,5,6)	S.E.	0.0024	0.0018	0.01	$1.07 \cdot 10^{-5}$
$n = 3$					
High	Mean	0.0280	0.0134	0.90	$1.18 \cdot 10^{-3}$
(Cells 7,8,9)	S.E.	0.0033	0.0017	0.12	$1.57 \cdot 10^{-4}$
$n = 3$					
Overall					
Mean		0.0323	0.0174	0.93	$1.22 \cdot 10^{-3}$
Std. Error		0.0025	0.0016	0.11	$1.42 \cdot 10^{-4}$

indicating that flow channels are not significantly affected by significant density increases up to 300 kg/m^3 and porosity decreases to 0.474 caused by compaction ratios of up to 2.9.

Initial K_{us}' average $1.74 \cdot 10^{-2}$ cm/s in contrast to ultimate K_{us}' which average $122 \cdot 10^{-3}$ cm/s, an order of magnitude less. The significant difference is consistent with observed channeling because initial apparent hydraulic conductivity reflects the conductivity of the most rapid flow in direct channels, whereas K_{us}' ultimate represents the sum of discharges through several active channels in the cell across section area A (0.255 m^2). Were only the actual flow channel areas used to estimate K_{us}' ultimate, the values would be within a factor of 2 to 3 of K_{us}' initial. These differences are relatively small compared to the 10^4 to 10^5 fold difference to HELP default value of $1.2 \cdot 10^{-7}$ cm/s for unsaturated conductivity of the waste layer. The low HELP default value stems in part from a low value for saturated hydraulic conductivity K_s ($2.0 \cdot 10^{-4}$ cm/s) and in part from the default values for residual soil moisture content RS, porosity n, and pore size distribution index λ, which determine, with the actual soil moisture content SM, the value of the correction term on the right hand side of equation 6. In order to compare this correction factor, the practical measured values for RS, n and λ are estimated below.

Similar to field capacities, apparent hydraulic conductivities were tested for correlation with density and porosity. Initial K_{us}' correlate very well with porosity (Pearson correlation coefficient = 0.91, $p = 0.001$) which reflects the dependence of hydraulic conductivity on porosity (see equation 2) because average velocity is essentially constant for all porosities and densities. Initial K_{us}' do not correlate with density. Ultimate K_{us}' do not correlate significantly with either porosity or density ($p = 0.98$ and $p = 0.81$). Therefore porosity may be a good indicator for apparent breakthrough conductivity, but neither density nor porosity predict channeled hydraulic conductivity well.

Bubbling pressure ψ_b and pore size distribution index λ, are estimated from the plot of log effective saturation versus log of capillary pressure (suction head). This plot was generated by using measured values for field capacity and air dried moisture content to calculate and plot effective saturation values with corresponding capillary pressure head values of 310 cm (0.3 atm), and 31,090 cm, the capillary pressure head for air dried municipal waste at shallow depths in landfills [9]. In contrast, the pore size distribution line is plotted for HELP default values in Figure 4. Practical bubbling pressure ψ_b' is less, at 15 cm, than the HELP value of 20.2 cm. The difference is as predicted due to flow following the wetting curve in channels through large interparticle pore spaces which lead to lower capillary pressures. Both reasons cause lower bubbling pressure for wetting in the waste column. The practical poresize distribution slope λ' is 0.67, and in the same order of magnitude as the HELP default λ of 0.21. However, small differences of λ can significantly affect effective saturation and ψ_b. Practical λ' indicates less pore size variation than the HELP default value. It is therefore very important to establish
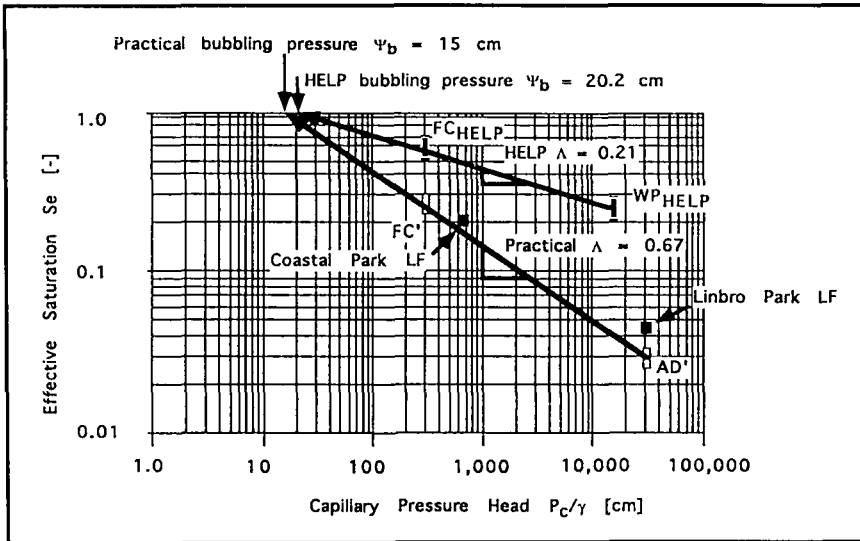
Figure 4. Effective saturation versus capillary pressure head
in municipal solid waste layer.

reliable values or predictive equations for λ. Finally, moisture content and corresponding capillary pressure head values reported for in-place municipal waste [9] are entered in Figure 4 and tend to coincide with the pore size distribution curve derived from the waste cell tests at both lower moisture (Linbro Park Landfill at lower right-hand) end as well as the high moisture content values near field capacity (Coastal Park Landfill, upper left).

Summary and Conclusions

Downward water flow through landfilled municipal solid waste occurs in narrow flow channels with a total area of 28 percent of the cross section area. The flow through solid waste layers does not appear to be one dimensional, uniform Darcian flow through a homogeneous medium. Rather, the flow occurs through narrowly confined, irregular channels.

Practical field capacity, the measure of the volume of water absorbed by the waste before free drainage occurs, was significantly lower, at 0.136, than the HELP model default value of 0.294 and than the measured average of 0.299 for drainage field capacity as defined by HELP. The difference stems from flow channeling and from the definition of the default value as a point on the drainage curve, whereas the practical value coincides with the wetting curve in unsaturated media. Measured porosity values of 0.58 to 0.47 coincide well with HELP default

value of 0.52, but vary with compaction ratio and with densities in the range of 170 to 305 kg/m^3.

Initial and ultimate apparent unsaturated hydraulic conductivities K_{us}' (initial) and K_{us}' (ultimate) are, at $1.74 \cdot 10^{-2}$ cm/s and $1.22 \cdot 10^{-3}$ cm/s, five and four orders of magnitude higher than the HELP default values ($1.2 \cdot 10^{-7}$ cm/s) and do not vary significantly with compaction ratio or density in the measured ranges. Initial K_{us}' correlates closely and significantly with porosity as a result of virtually constant flow velocity (0.0323 cm/s) and of porosity values that correlate significantly with compaction ratio.

As a result of lower practical field capacity and of low air dried moisture content of waste, the log of effective soil moisture versus log of suction head curve produces a slightly lower value for practical bubbling pressure ψ_b' of 15 cm (versus HELP's 20.2 cm) as expected for channeled flow and a slightly higher practical pore size distribution index of λ' of 0.67 (versus HELP's 0.21). The correction factor applied to the saturated hydraulic conductivity K_s of

$$\left[\frac{SM - RS}{n - RS}\right]^{3 + \frac{2}{\lambda}} \tag{7}$$

is approximately ten times smaller (at $5.93 \cdot 10^{-5}$) for practical field capacity FC', porosity n and pore size distribution index λ' than for HELP values ($6.0 \cdot 10^{-4}$). As a result, the apparent practical, channeled saturated hydraulic conductivity of waste is 10^5 to 10^6 larger than the HELP default values of $2.0 \cdot 10^{-4}$ cm/s.

Flow channeling and resulting flow characteristics indicate that leachate leakage from the waste layer is bound to occur more rapidly and at higher flow rates than predicted with HELP and its default values. Particularly during the active landfilling phase, when cell cover is minimal, the velocity and leakage rates are higher by 10^4 and breakthrough times are lower by 10^5. As a result, leachate head on the liner and leachate flow to the collection and treatment system will be greater and will occur sooner than previously predicted. For example, the practical breakthrough time for a 2 meter thick layer of MSW would be predicted as 6,092 sec (1.7 hrs). The leakage rate Q_{lk} for a 100 m^2 cell surface area would be $1.22 \cdot 10^{-3}$ m^3/s versus the HELP value of $1.2 \cdot 10^{-7}$ m^3/s.

Channeling effects mean that biodegradation of landfilled waste may occur preferentially along wetted channels where flow, nutrient transport and waste product removal is intensive while large pockets of waste remain relatively dry. Although observed moisture in dry areas is sufficient to support biological activity [9], rates are bound to be lower.

The following actions are recommended based on the research results:

1. The default values for field capacity and dry points should be adjusted downwards to fit measured values on the wetting curve.

2. Porosity values should be listed as a function of compaction ratio of the waste.

3. Additional tests should be conducted of moisture flow over longer test periods to verify the channeling behavior and characteristic values (field capacity, low moisture point, porosity, etc.). Further, the changes due to settlement and biodegradation should be tested and specified, particularly for the early stages of landfilling (one to five years) when changes occur rapidly.

4. The Darcian flow model should be revised to account for channeling in the early stages of flow development and possibly combined with Darcian moisture front movement in later stages.

NOTATIONS LIST

A	= Cross sectional area of test cell, here 0.255 cm^2
AD	= Air dried moisture content, [-]
CR	= Compaction Ratio [Vol. initial/Vol. final]
FC$_H$	= Field capacity as measured for drainage curve in HELP, [-]
FC'	= Practical field capacity as measured for channeled flow
FlCh	= Practical area of flow channeling, as fraction of total cross section area A, [-]
h	= Height of waste layer in test cells [m]
$\frac{dh}{d}$	= hydraulic gradient, equals unity for downward flow in waste layer, [-]
K$_s$	= hydraulic conductivity (saturated), $\left[\frac{cm}{s}\right]$
K$_{us}$' (initial)	= initial apparent unsaturated hydraulic conductivity, effective from the time of first infiltration until breakthrough, $\left[\frac{cm}{s}\right]$
K$_{us}$' (ultimate)	= ultimate apparent unsaturated hydraulic conductivity after flow has been established, $\left[\frac{cm}{s}\right]$
n	= porosity [-]
q	= specific discharge, $\left[\frac{cm}{s}\right]$
Q	= discharge rate = q · A [L/s]
Rosin-Rammler n	= particle size distribution index, [-]
RS	= Soil moisture content at residual saturation, the ratio of moisture volume to total soil (waste) volume at the point where permeability to the wetting fluid, here water, equals zero, [-]

S_e = effective saturation = $\dfrac{SM - RS}{n - RS}$

SM = Soil moisture content, [-]

t_{bt} = breakthrough time, [s]

$\bar{v}$ = Average flow velocity, $\left[\dfrac{cm}{s}\right]$

X_o = Characteristic particle size, [cm]

WP = Soil moisture content at wilting point (P = 15 atm)

ψ = capillary pressure $\left(= \dfrac{P_c}{\gamma}\right)$, [cm]

ψ_b = bubbling pressure, minimum capillary pressure on the drainage cycle for which a continuous non-wetting (here: air) phase exists [cm]

ρ_w = waste density, [kg/m^3]

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Direct reprint requests to:

Professor Chris Zeiss
Department of Civil Engineering
University of Alberta
Edmonton, Alberta T6G 2G7