J. ENVIRONMENTAL SYSTEMS, Vol. 30(3) 233-253, 2003-2004

RICHARDS EQUATION FEASIBILITY IN PREDICTING FLOW IN UNSATURATED SOLID WASTE AT A SEMI-ARID TROPICAL LANDFILL

J. CAPELO

M. A. H. DE CASTRO

Federal University of Ceara, Brazil

ABSTRACT

The validity of a model that calculates one-dimension, one-phase, vertical transient water flow through unsaturated Municipal Solid Waste (MSW) was verified by comparing the simulated results against data obtained in a new field experiment. The experimental data consisted of absolute moisture profiles that changed over time from columns packed with real solid wastes, measured by a Neutron Probe, and subjected to an artificial intense rain event. The artificial rain tried to simulate the precipitation intensity present in a semi-arid tropical region, The results showed that in order to adjust to the experimental curves, the field capacity had to be increased during the simulation by changing the characteristic equation empirical parameter α_{cf}. It was also found that, when used in the simulation process, the measured hydraulic conductivity at saturation ($K_s = 1.71 \times 10^{-04}$ cm/sec) was not able to represent the experimental unsaturated flow. Only by attributing large values to K_s (such as 10,000 cm/hr), was it found a good fit to the experimental curves. Although it was possible to mimic them using the Richards equation, it is evident that the conceptual model used is not a physically sound representation of the observed phenomenon.

INTRODUCTION

Landfills are the dominant means of disposing of solid waste for almost all developing countries because of their relative simplicity, low cost, and easy management. Although implementation of waste reduction, recycling, and transformation technologies have been decreasing dependency on landfills, they remain important components of an integrated solid waste management.

One of the greatest concerns on the impacts of an existing or a proposed landfill is the groundwater pollution caused by leachate. Even small quantities of landfill leachate can pollute large amounts of groundwater, rendering them unusable for domestic and many other purposes. Therefore, further understanding of leachate flow pattern inside Municipal Solid Waste (MSW) should contribute to a decrease in the risk of groundwater pollution.

Moreover, enhanced biological activity of MSW in landfills can accelerate stabilization of its organic fraction, increasing biogas recovery and reducing long-term potentially hazardous environmental impacts. Moisture content is one of the most important factors in controlling solid waste bioactivity. In order to maintain the ideal moisture content, solid waste hydraulic properties and leachate flow characteristics should be correctly understood to properly design leachate collection and recycling systems.

Predictive modeling within landfills requires an understanding of moisture movement through solid waste layers. Many researchers' efforts have been devoted to predicting moisture flow. Several methods and computer models have been developed, falling into two general categories: deterministic water balance [1-4] and finite-difference/finite-element methods [5-10]. In the water balance method, leachate production is calculated by subtracting runoff, evapotranspiration, and change in of water storage in the earthen cover and waste layers, from precipitation. However, the internal moisture flow process is not taken into account considering landfill a "black box."

Finite-difference/finite-element methods use the classical theory of unsaturated flow through porous media to predict moisture flow in landfills. This theory is based on Richards [11] equation, a nonlinear second-order partial differential equation, which can be used to characterize flow in the unsaturated zone of a landfill. An exact analytical solution can be obtained by making simplifying assumptions, however this procedure limits the representation of the real flow. Numerical solutions of the Richards equation can approximate realistic field applications under various conditions where the assumptions needed for analytical solutions are not valid. These techniques were described by Gardner and Mayhugh [12], Remson et al. [13], Rulon et al. [14], and Celia et al. [15].

The objective of the present work is to evaluate the applicability of Richards equation to vertical one-dimensional, one-phase moisture flow in unsaturated municipal solid waste by comparing it to a series of experimental data. The experimental data used was obtained by a new experimental procedure [16] that used a neutron probe to measure transient moisture flow in a non-destructive form, inside columns packed with unsaturated MSW during an artificial rain event.

LITERATURE REVIEW

Straub and Lynch [5] developed a mathematical model to predict contaminant and moisture transport in unsaturated landfills. The model was based on the theory of unsaturated flow and transport in porous media. An explicit finite-difference solution was used to numerically solve the equations. The empirical parameters and the relations for unsaturated hydraulic conductivity and for tension head were obtained from soil physics. They assumed that the waste was composed mostly of paper and fibrous materials. Vertical moisture profiles and leachate outflow in various times were simulated and then compared to experimental leachate production data obtained by other researchers. The comparison between simulated and experimental data demonstrated that it was feasible to analyze compacted solid waste as an unsaturated porous medium, but the authors suggested that additional experimental work should be required to identify and refine the basic processes of moisture flow in landfills.

Korfiatis et al. [6] employed the theory of unsaturated flow through homogeneous and isotropic porous media to analyze leachate flow patterns in a solid waste laboratory column. Intrinsic hydraulic characteristics of the solid waste were determined experimentally. The volume of leachate outflow and suction heads at several elevations in the column were measured. The vertical one-dimensional equation for downward flow through an unsaturated porous medium was solved numerically by a fully implicit finite-difference scheme. The experimental phase consisted of a refuse column instrumented with tensiometers, subjected to controlled surface moisture input to simulate rainfall, and an outlet drain to measure leachate outflow. The volume of leachate collected at the bottom of the column and the time history of the suction pressure inside along the column were measured. The mathematical model was then calibrated with the results obtained in their experiment. The authors concluded that the model responded well to changes in precipitation rates and predicted leachate discharge without any significant time lagging. Although the comparison of the measured and computed cumulative volumes agreed well, a difference as high as 25% was observed between measured and computed discharge rates. The time history of the suction pressure along the column was not presented in this work.

The vertical flow of an incompressible fluid through a homogeneous, non-deformable, unsaturated porous medium was studied by Demetracopoulos et al. [7]. They used an equation obtained from a combination of the Continuity and Darcy's law (modified Richards equation) to simulate fluid flow in a conceptual landfill. They also performed a detailed sensitivity analysis in order to investigate the effects of the parameters associated with the simulated solution. A fully implicit scheme was used to solve numerically the governing equation. The variation of grid size and time step did not have a significant effect on the simulated moisture profile. On the other hand, changes in the hydraulic conductivity and in the empirical parameter B from the hydraulic conductivity function, demonstrated a strong influence in the results. The authors agreed that the model could be used to evaluate the leachate quantities produced by an existing or inactive landfill. However, the simulated results were not validated with field or laboratory scale experimental data and therefore, may not be considered a consistent approach.

Noble and Arnold [8] studied flow in experimental columns filed with artificial solid waste using the FULFILL model. The experimental apparatus was formed by a constant, head, glass column (40.7 cm in length and 4.7 cm internal diameter) packed with 1.27 cm squares of dry newspaper with dry density of 334.8 kg/m^3 to the height of 30.5 cm. The measurements taken consisted of breakthrough time, volume of water collected over time, and newspaper mass at the end of the experiment. The FULFILL program is a one dimensional, finite-difference computer model based on the Richards equation for one-phase, unsaturated flow through homogeneous porous media. The authors concluded that Richards equation reasonably described moisture transport in the laboratory scale apparatus, provided that appropriate constitutive laws and adjustable parameters were used. However, as stated by the authors, the use of small pieces of paper to simulate MSW prevented flow from channeling through the column. It has been demonstrated by Zeiss and Uguccioni [17] that channeling flow plays an important role in the overall moisture transport in real solid waste, therefore any experiment or model that does not consider this phenomenon may misrepresent water flow in real landfills.

Ahmed et al. [9] developed a numerical model to simulate unsteady leachate flow in landfills. Two-dimensional Richards equation was solved using an implicit finite-difference scheme. Runoff, evapotranspiration, and infiltration were used as boundary conditions. The kinematic wave equation was used to calculate runoff considering the effect of slope and surface roughness, and the modified Panman method was used to determine evapotranspiration. The model was then used to simulate leachate production in the Fresh Kills Landfill, New York. The output data was compared to the results obtained by the HELP model [4], showing a good approximation. A rigorous validation of the applicability of Richards equation to flow in solid waste was not presented in the article. Furthermore, the combination of the many sub-models and assumptions used to calculate runoff, evapotranspiration, and infiltration may have dimmed Richards equation's suitability in simulating transient flow in solid waste.

Khanbilvardi et al. [10] developed a two-dimensional, unsteady-state model called FILL (Flow Investigation for Landfill Leachate). This model simulates moisture content in a porous media vertical profile. The authors applied the field condition of a real landfill to FILL and HELP models and compared the outputs to results obtained in previous modeling efforts which used Darcy's law and the EPA water-balance method [1], to verify the validity of the new model. An implicit finite-difference scheme was used to solve the partial differential equation and compute moisture content in the solid waste vertical section. The conditions considered were free drainage due to gravity for the lower and precipitation less surface runoff and evapotranspiration for the upper boundary, The evaporation was computed by the modified Panman method and the runoff by the kinematic wave equation. The model (FILL) calculated a lower leachate outflow compared to HELP, to water balance, and steady state (Darcy's law) models and it indicated a greater accumulation of leachate in the leachate mound. Although the authors considered that the model represented field conditions more realistically, the simulated results were not validated by comparing them with real landfill leachate production data and, therefore, cannot be confirmed as a more realistic estimation. It is also evident that the difficulties in validating Richards equation come from uncertainties in estimating the evapotranspiration and runoff processes.

MATERIAL AND METHODS

Experimental Procedure

Capelo [16] constructed three leaching columns (60 cm ID by 3 m high) to simulate vertical moisture movement in a Municipal Solid Waste (MSW) landfill located in a semi-arid tropical region. Flow in the solid waste layer was investigated in an isolated form, without the influence of an impermeable layer, evapotranspiration, and runoff. A draining system was built at the bottom of each column, and at the center an aluminum pipe was installed. The MSW sample was weighted and packed in successive layers of 20 cm until reaching a density of 550 kg/m^3 (compacted density of the waste at the local landfill). Only 240 cm of the columns were occupied.

An aspersion system was installed with the objective of simulating precipitation over the solid waste, adding water in a controlled and distributed form. The flow density applied was 9.50 cm/hr in column one and 14.25 cm/hr in columns two and three. Those flow densities were chosen in order to represent the precipitation intensity present in the studied sanitary landfill area (a semi-arid tropical region). A neutron probe was used to measure moisture content in the solid waste columns. Readings were taken approximately every 25 minutes, taking approximately 30 seconds per 30 cm layer. The experiment developed was capable of measuring absolute and change in moisture content in the solid waste in a non-destructive form during a simulated precipitation event. The mean measured saturated hydraulic conductivity was $K_s = 1.71 \times 10^{-04}$ cm/sec. The residual saturation ($\theta_r = 13\%$ v/v) and moisture at saturation ($\theta_s = 41\%$ v/v) were also determined experimentally.

The author concluded that, at saturation, the water flow in all three columns behaved in a manner compatible with Darcy's flow. However, Darcy's law apparently did not physically represent the water flow in non-saturated solid waste due to the presence of greatly interconnected macro-pores or preferential pathways. Moreover, it seemed that a determined layer did not need to reach a defined moisture content, referred as *field capacity,* in order to allow water through it. In fact, the definition of *field capacity* seemed to apply poorly in the case of moisture flow through solid wastes.

Simulation

The software CHEMFLO™–2000, Interactive Software for Simulating Water and Chemical Movement in Unsaturated Soils [18] was used to simulate water movement in unsaturated MSW. Water movement is modeled by solving a one-dimensional Richards equation (1) using the finite-differences method. The required soil hydraulic properties are defined by specifying the θ(h) and K(h) functions. The objective of the simulation was to adjust the calculated moisture profiles to the data obtained in the field experiment [16]. The part of the program that dealt with chemical movement was not used in this work.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\left(\frac{\partial h}{\partial x}-sen(A)\right)\right]$$

or

$$C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\left(\frac{\partial h}{\partial x}-sen(A)\right)\right] \tag{1}$$

Where:

θ = θ(h) → is the volumetric water content;

h = h(x,t) → is the matric potential;

x → is the position parallel to the direction of flow;

t → is the time;

sin (A) → is the sine of the angle A between the direction of flow and the horizontal direction;

K(h) → is the hydraulic conductivity of the soil at matric potential h;

C(h) = dθ/dh → is the specific water capacity.

CHEMFLO defines soil properties using the conductivity [12, 19, 20] and water characteristic [19-21] equations. The present work used the Van Genuchten equations [20] for characteristic functions (2) and hydraulic conductivity (3) because they adjusted well to the experimental results developed in solid waste by Benson and Wang [22].

$$\theta(h)=\theta_r+\alpha\frac{\theta_s-\theta_r}{[1+(\alpha|h|)^n]^m} \quad \text{for } h<0$$

$$\theta(h)=\theta_s \quad \text{for } h\geq 0 \tag{2}$$

Where:

θ(h) → volumetric water content at matric potential h;

θ_r → residual water content;
θ_s → saturated water content;
α → empirical constant;
n → empirical constant.

$$K(h) = K_s \frac{\left\{1 - (\alpha|h|)^{n-1}\,[1 + (\alpha|h|^n\;)]^{-m}\right\}^2}{} \qquad \text{para } h < 0$$

$$K(h) = K_s \qquad \text{para } h \geq 0 \tag{3}$$

Where:
K(h) → hydraulic conductivity at matric potential h;
KS → saturated hydraulic conductivity;
α → empirical constant;
n → empirical constant.

The CHEMFLO software can simulate moisture movement in soil columns of finite length with uniform or non-uniform initial conditions and in semi-infinite soils with uniform initial conditions. Four types of boundary conditions can be applied at the soil surface: constant potential, constant flux, mixed type, and falling head. For a finite soil system, the boundary conditions that can be imposed at x = L are constant potential, constant flux, or free drainage. Flux density q (x, t) of water is given by the Darcy-Buckingham equation (4). The computational methods used to solve the Richards equation is based on the work of Celia et al. [15] which has the advantage of maintaining mass balance of water in the system.

$$q(x,t) = K(h)\frac{\partial H}{\partial x} \tag{4}$$

Where H is the total potential of the soil water.

The data used in this work to run the program are presented as follows:

1. Layer thickness—The simulated columns had a total length of 240 cm. In order to represent the heterogeneities observed in the experimental runs, it was necessary to design the simulated columns with five different layers (the maximum number allowed by the program), attributing different hydraulic conductivities to each one of them (Figure 1). Layer thickness was determined so that their interfaces were positioned where water accumulation was encountered in the experiments.

2, Hydraulic conductivity at saturation (K_s)—Although this parameter was determined in the field experiment (K_s = 1.71 × 10^{-04} cm/sec), it would not adjust the simulated curves to the measured ones. Therefore, new hydraulic conductivities had to be found. The saturated hydraulic conductivity attributed to each layer was determined by trial and error. A sensitivity analysis was performed by changing this parameter to verify the effects of the variations in the simulated curves.

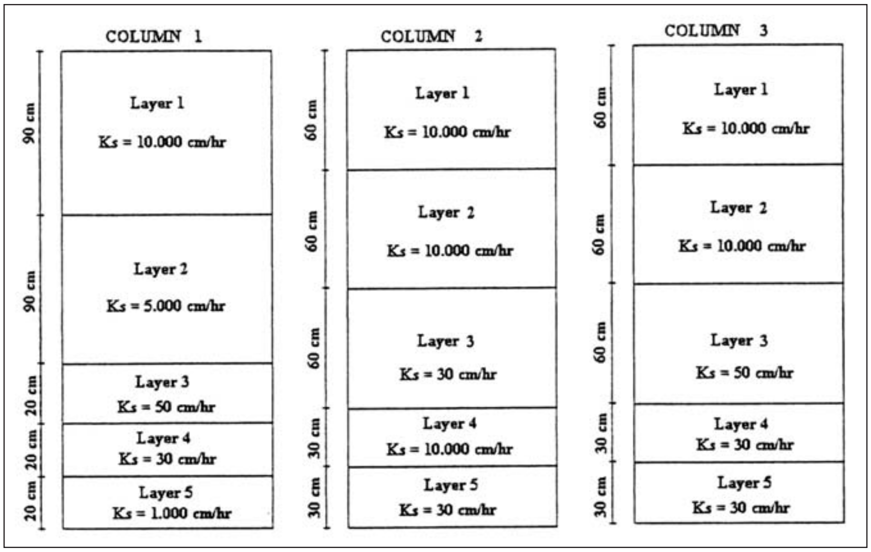

Figure 1. Simulated columns subdivision in five layers, attributing to each layer different saturated hydraulic conductivity.

3. Uniform volumetric water content of 13% v/v (residual saturation) was chosen as the initial condition (*t* = 0). The boundary conditions used were: Constant flux at x = 0 cm equal to the density of flow of the experimental apparatus (q_1 = 9.50 cm/hr for column 1 and q_2 = 14.25 cm/hr for column 2 and 3), and equal to zero at x = 240 cm. The flow density at x = 240 was defined as zero because the column draining system was kept close during this part of the experiment. These parameter and moisture at saturation ($\theta_s = 41\%$ v/v) were kept constant during the simulation process.

4. The empirical parameters (α_{wcf}, η_{wcf}, α_{cf}, and η_{cf}) of the Van Genuchten hydraulic conductivity and characteristic functions were determined by trial and error during the simulation. A sensitivity analysis was performed by changing those parameters to verify the effects of the variations in the simulated curves.

5. An angle of inclination of 90° was kept constant.

RESULTS AND DISCUSSION

Sensitivity Analysis

Figure 2 shows the advance of the wetting front from 0.5 to 2.67 hours, using the measured hydraulic conductivity at saturation ($K_s = 1.71 \times 10^{-04}$ cm/sec) and

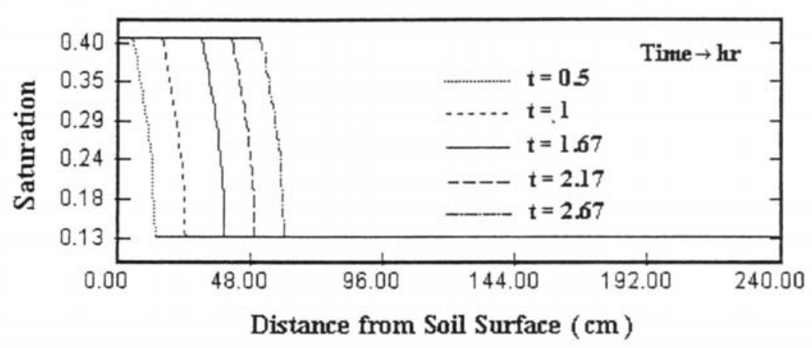

Figure 2. Wetting front advance with time (*t* in hours) using the measured hydraulic conductivity at saturation (Ks = 0,618 cm/hr) keeping all the other parameters constant.

maintaining all other parameters constant. It was observed that the simulated wetting front velocity was much slower than the velocity observed in the field experiment. Because of that, a substantial increase in the saturated hydraulic conductivity was necessary to approximate the simulated curves to the experimental ones.

The hydraulic conductivity at saturation was varied keeping all other parameters constant. The effects of this variation for $t = 1$ hour is shown in Figure 3. It was observed that by increasing the conductivity from 1 to 10,000 cm/hr, the wetting front velocity increased, making it possible for moisture to reach deeper into the waste column. The curve with a similar wetting front velocity to the experimental curve is the one associated with the hydraulic conductivity of K_s = 10,000 cm/hour. Analyzing it in terms of porous matrix infiltration, this conductivity would be absurdly high and with no physical meaning. However, when the presence of the preferential pathways is taken in to consideration, this conductivity starts to represent, in an equivalent form, another physical process of flow.

The variation of α_{cf} and n_{cf} over time, maintaining all the other parameters constant (Figures 4 and 5), affected the field capacity or moisture accumulation in the solid waste. Increasing α_{cf} from 0.02 at $t = 0.5$ hour to 0.055 at $t = 2.67$ hours resulted in a moisture increase in the layers above the wetting front from about 19 to 25% v/v. Increasing n_{cf} from 2.0 at $t = 0.5$ hour to 3.0 at $t = 2.67$ hours resulted in a moisture increase in the layers above the wetting front from about 19 to 21% v/v.

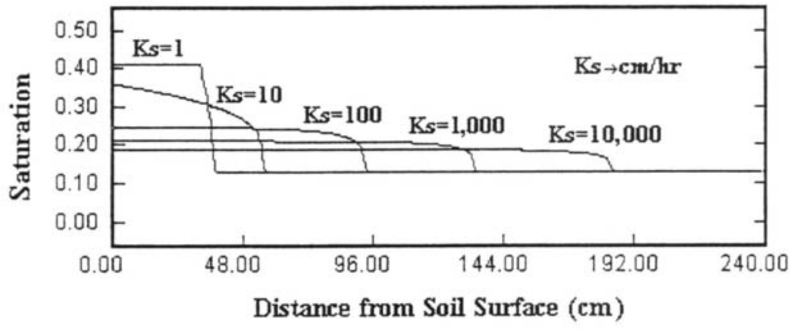

Figure 3. Parameter Ks sensitivity analysis, at *t* = 1 hour and keeping all the other parameters constant.

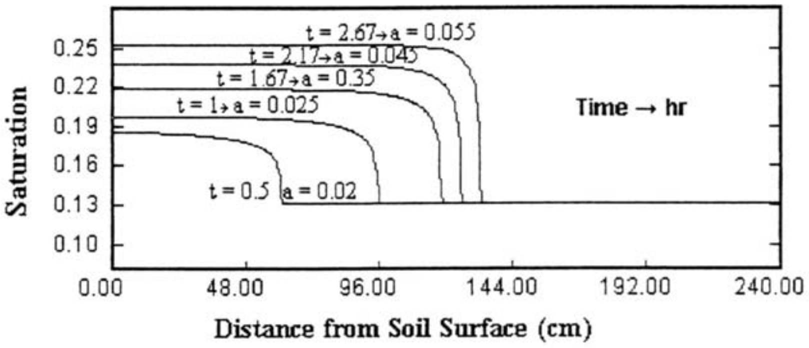

Figure 4. Parameter α_{cf} sensitivity analysis, changing time from *t* = 0.5 to *t* = 2.67 hours, and keeping all the other parameters constant.

The variation of α_{wcf} and n_{wcf} over time, maintaining all the other parameters constant (Figures 6 and 7), also affected the field capacity or moisture accumulation in the solid waste. Decreasing α_{wcf} from 0.1 at *t* = 0.5 hour to 0.035 at *t* = 2.67 hours resulted in a moisture increase in the layers above wetting front from about 17 to 23% v/v. Decreasing n_{wcf} from 3.0 at *t* = 0.5 hour to 1.25 at *t* = 2.67 hours resulted in a moisture increase in the layers above wetting front from about 16 to 21% v/v.

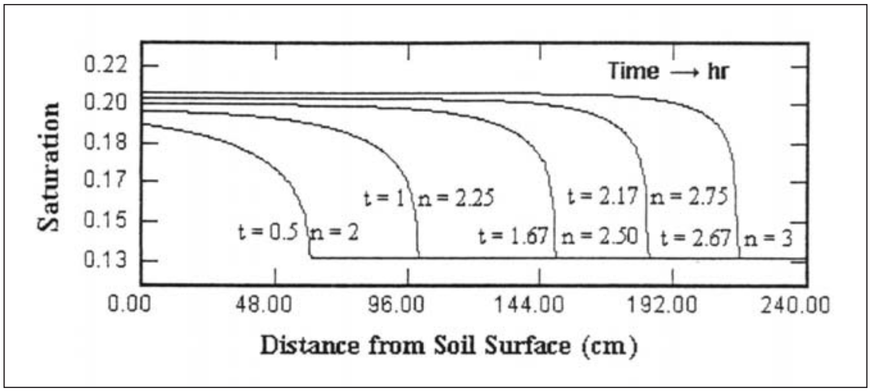

Figure 5. Parameter η_{cf} sensitivity analysis, changing time from t = 0.5 to t = 2.67 hours, and keeping all the other parameters constant.

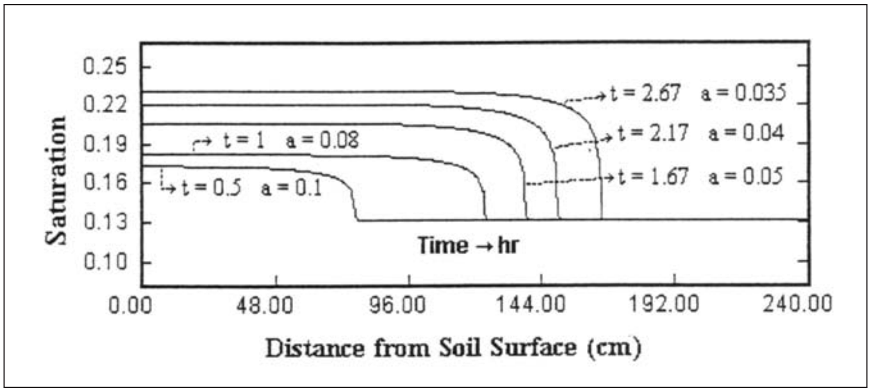

Figure 6. Parameter α_{wcf} sensitivity analysis, changing time from t = 0.5 to t = 2.67 hours, and keeping all the other parameters constant.

The sensitivity analysis of the empirical parameters showed that their variation affected the solid waste field capacity or the solid waste capacity to keep absorbing moisture in the layers above the wetting front. In summary, an increase on α_{cf} or n_{cf} and a decrease of a α_{wcf} or n_{wcf}, increased the solid waste capacity of moisture accumulation. As observed in the field experiment, moisture increased with time in the layers above the wetting front and therefore, it was necessary to use the variation of one of these parameters in order to simulate the experimental curves. Parameter α_{cf} was chosen for this purpose.

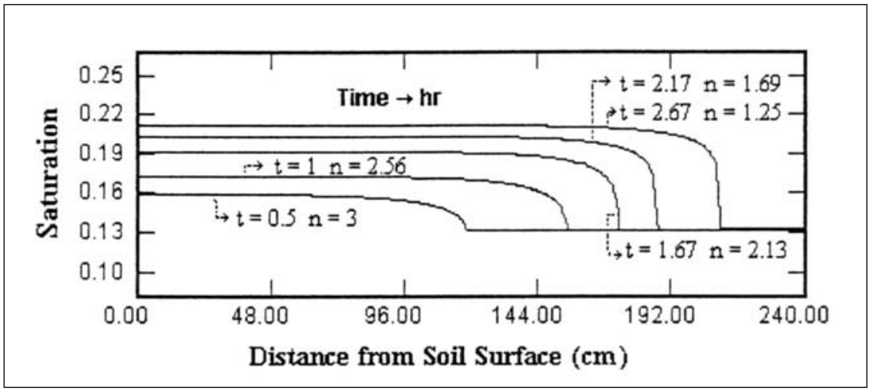

Figure 7. Parameter η_{wcf} sensitivity analysis, changing time from $t = 0.5$ to $t = 2.67$ hours, and keeping all the other parameters constant.

Figures 8, 9, and 10 show fitting of the simulated curves (lines) to the experimental curves (points) in columns 1, 2, and 3 respectively. The empirical parameters kept constant were $n_{cf} = 2.9$, $n_{wcf} = 1.875$, and $\alpha_{wcf} = 0.05$. Despite the long time taken in the curve fitting process, the artifice used was able to adjust the simulated curves in a satisfactory manner as shown by the chi square hypothesis test (χ^2) presented in Tables 1, 2, and 3.

It is observed in Figure 11 that, in layers one and two of column 1, subjected to moisture increase right at the beginning of the experiment, the parameter α_{cf} had nearly a linear variation with time. On the other hand, this parameter practically remained unchanged in the lower layers (3, 4, and 5) until about 3.5 hours. From that time on, α_{cf} also experienced a linear increment but with a larger inclination then the upper layers. The delay on the α_{cf} increment in the lower layers was probably due to the late moisture arrival, and the larger speed of increment for longer times, due to water accumulation in the lower part of the column, which remained closed. The α_{cf} variation pattern observed in column 1 was also observed in columns 2 and 3, although that with lesser level of detailing (Figures 12 and 13).

If this behavior had been observed in a porous medium such as soil, it could be concluded that the medium characteristics were changing with the time. However, in solid wastes, it is not believed to be the case. This research suggests that the solid waste matrix is surrounded by wide preferential pathways, through which the water can flow freely on the particles surface in the form of a free film. Moreover, moisture accumulation would occur because of the absorption and diffusion of this water into the solid waste matrix. The absorption and diffusion processes would be a function of the film thickness on the solid waste surface and, therefore, a function of the applied flow density.

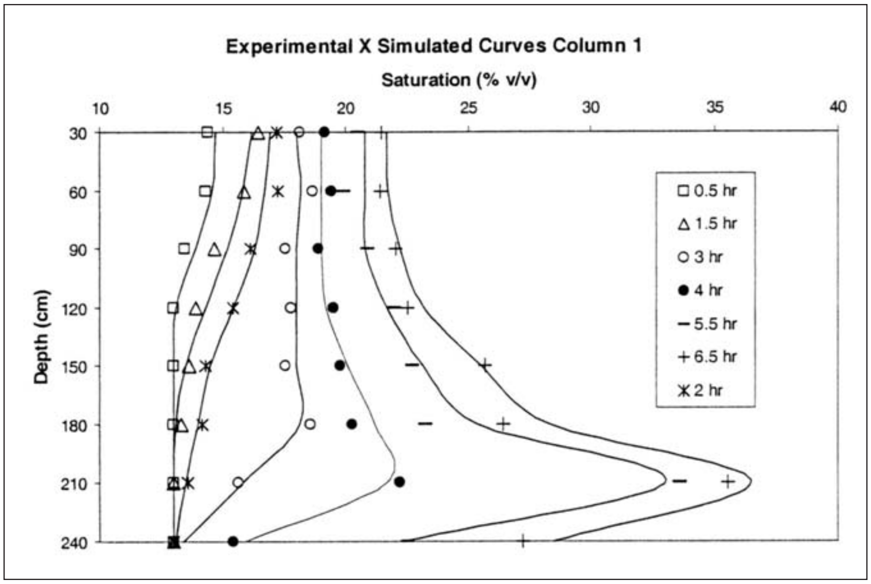

Figure 8. Simulated curves (lines) fit to the experimental curves (points) in column 1.

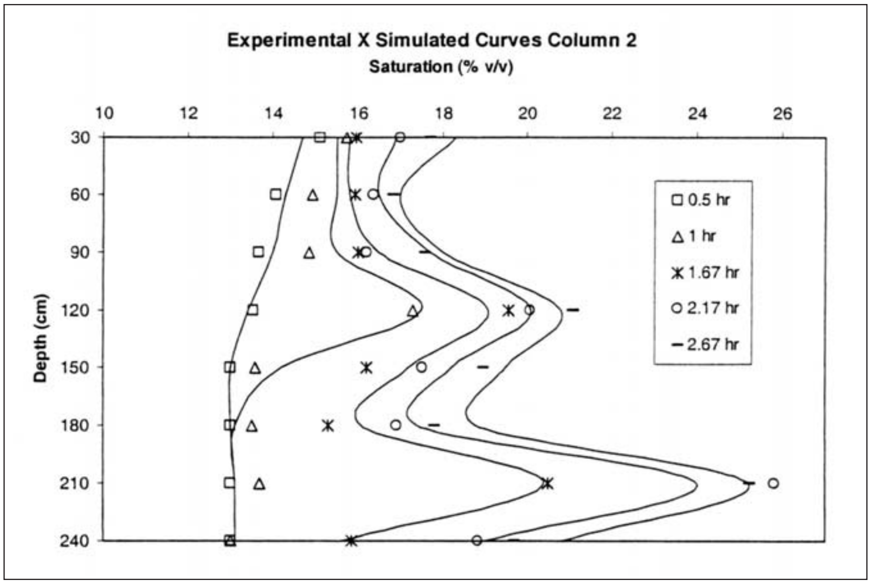

Figure 9. Simulated curves (lines) fit to the experimental curves (points) in column 2.

Table 1. Simulated Approximation to Experimental Curves and Hypothesis Test Results in Column 1

Time	0.5 hr		1.5 hr		2 hr		3 hr		4 hr		5.5 hr		6.5 hr	
Depth (cm)	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.
30	14.40	14.70	16.43	16.20	17.21	16.95	18.12	18.00	19.14	19.01	20.48	20.80	21.45	21.70
60	14.30	14.60	15.85	15.80	17.23	16.70	18.68	18.20	19.40	19.01	19.92	20.80	21.44	21.75
90	13.47	13.90	14.67	15.20	16.13	16.30	17.54	18.00	18.90	19.02	20.87	20.80	22.05	22.20
120	13.00	13.10	13.93	14.30	15.41	15.40	17.77	18.00	19.51	19.20	21.97	21.70	22.54	23.20
150	13.00	13.00	13.66	13.50	14.32	14.50	17.55	18.00	19.77	20.10	22.73	23.15	25.70	25.50
180	13.00	13.00	13.35	13.10	14.18	14.00	18.56	18.12	20.27	21.20	23.23	25.40	26.43	28.30
210	13.00	13.00	13.00	13.00	13.59	13.50	15.64	15.80	22.23	21.70	33.58	33.00	35.56	36.50
240	13.00	13.00	13.00	13.00	13.00	13.10	13.00	13.40	15.43	15.90	22.54	22.30	27.24	28.50
χ^2	0.99999998		0.99999991		0.99999997		0.99999950		0.99999838		0.99992983		0.99994912	

Table 2. Simulated Approximation to Experimental Curves and Hypothesis Test Results in Column 2

Time	0.5 hr		1 hr		1.67 hr		2.17 hr		2.67 hr	
Depth (cm)	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.
30	15.10	14.70	15.74	15.50	15.95	15.80	16.99	16.90	17.69	18.30
60	14.07	14.30	14.93	15.50	15.95	15.80	16.35	16.50	16.81	17.00
90	13.66	14.00	14.84	15.50	16.00	16.50	16.22	17.70	17.58	18.00
120	13.54	13.40	17.30	17.50	19.58	19.10	20.07	20.10	21.09	20.80
150	13.00	13.00	13.58	14.20	16.21	17.20	17.52	18.20	18.96	19.50
180	13.00	13.00	13.51	13.10	15.31	16.10	16.93	17.40	17.82	18.80
210	13.00	13.10	13.68	13.10	20.50	20.40	25.80	24.00	25.23	25.20
240	13.00	13.10	13.00	13.10	15.86	15.60	18.85	19.00	19.70	20.80
χ^2	0.999999978		0.999995374		0.999993303		0.999896136		0.999986106	

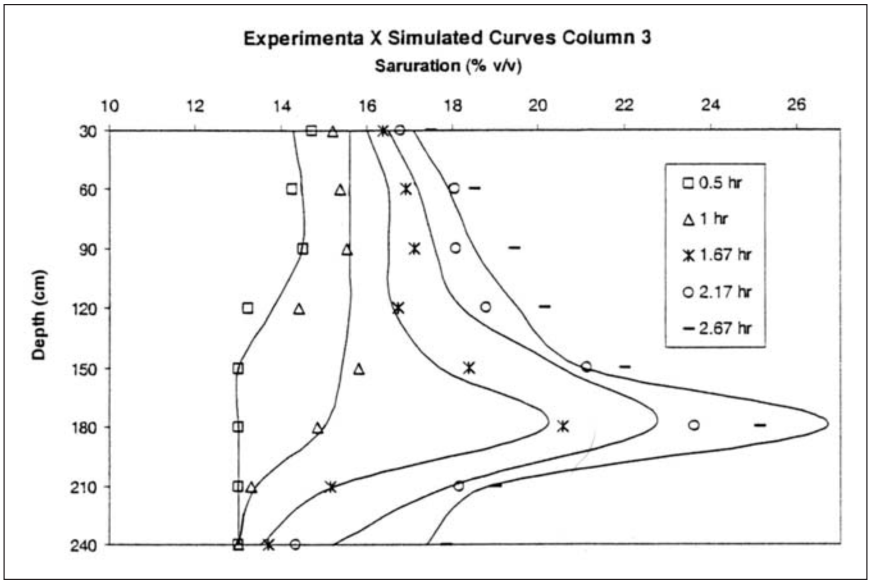

Figure 10. Simulated curves (lines) fit to the experimental curves (points) in column 3.

CONCLUSIONS

The variation of Van Genuchten empirical parameters (α_{cf}, n_{cf}, α_{wcf}, and n_{wcf}) affected the amount of water each solid waste layer could store. In order to fit the simulated curves, the solid waste field capacity had to be increased by varying one of those parameters, making the definition of field capacity poorly applicable to the studied medium.

When the measured hydraulic conductivity at saturation (K_s) was used in the flow simulation, a very slow wetting front resulted and did not represent the experimental behavior. The K_s sensitivity analysis showed that, only by attributing large values to K_s (such as 10,000 cm/hr), it was possible to find a good approximation to the experimental curves. This result reinforces the theory of that the solid waste is a micro-porous medium crossed by highly interconnected preferential pathways.

The heterogeneity observed in the experimental runs was confirmed during the simulation procedure. In order to get a good adjustment of the experimental curves, it was necessary to attribute different hydraulic conductivities (K_s) to the column layers from a relatively low value (30 cm/hr) to a significantly high value (10.000 cm/hr).

The variation of the empirical parameter α_{cf} was approximately linear in the upper layers. In the lower layers, it practically did not change in the initial

Table 3. Simulated Approximation to Experimental Curves and Hypothesis Test Results in Column 3

Time	0.5 hr		1 hr		1.67 hr		2.17 hr		2.67 hr	
Depth (cm)	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.	Exper.	Simul.
30	14.71	14.30	15.21	15.60	16.38	16.00	16.79	16.50	17.48	17.10
60	14.27	14.50	15.38	15.60	16.90	16.50	18.05	17.20	18.49	17.90
90	14.51	14.50	15.52	15.60	17.12	16.50	18.07	17.60	19.44	18.50
120	13.22	13.80	14.41	15.60	16.73	16.60	18.78	18.20	20.14	19.50
150	13.00	13.00	15.79	15.40	18.37	17.70	21.13	20.50	22.01	21.00
180	13.00	13.00	14.85	15.00	20.58	20.20	23.62	22.70	25.14	26.70
210	13.00	13.00	13.31	13.40	15.14	15.20	18.15	17.90	19.01	18.80
240	13.00	13.00	13.00	13.00	13.71	13.50	14.35	15.20	17.85	17.40
χ^2	0.999999897		0.999995094		0.999999085		0.999981158		0.999946354	

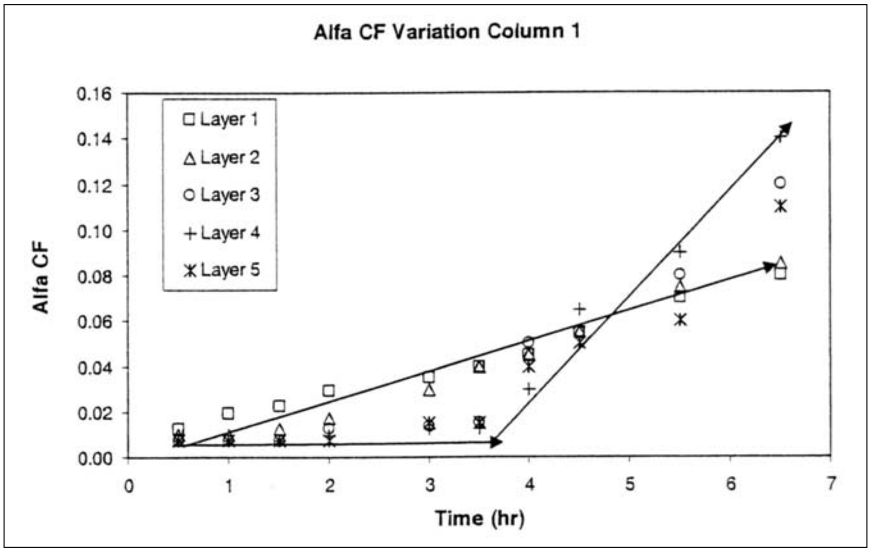

Figure 11. α_{cf} variation pattern observed in column 1 during the fitting process.

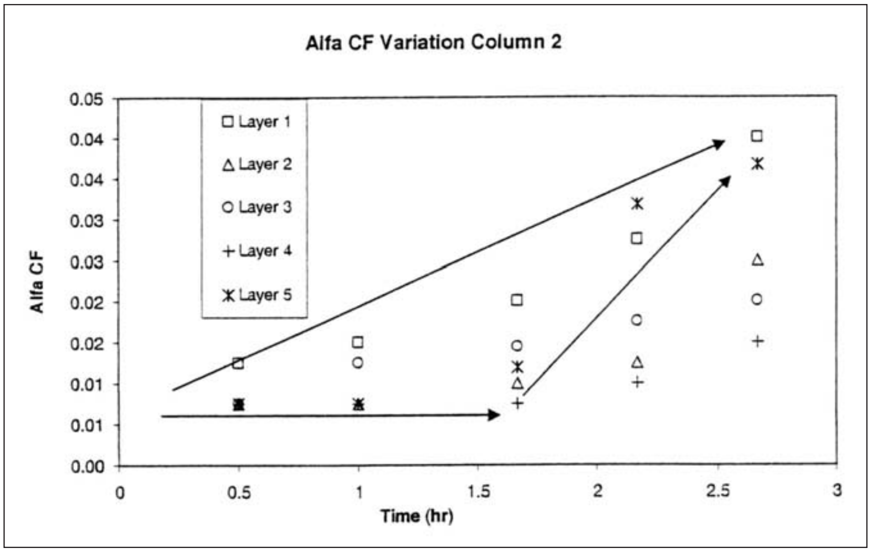

Figure 12. α_{cf} variation pattern observed in column 2 during the fitting process.

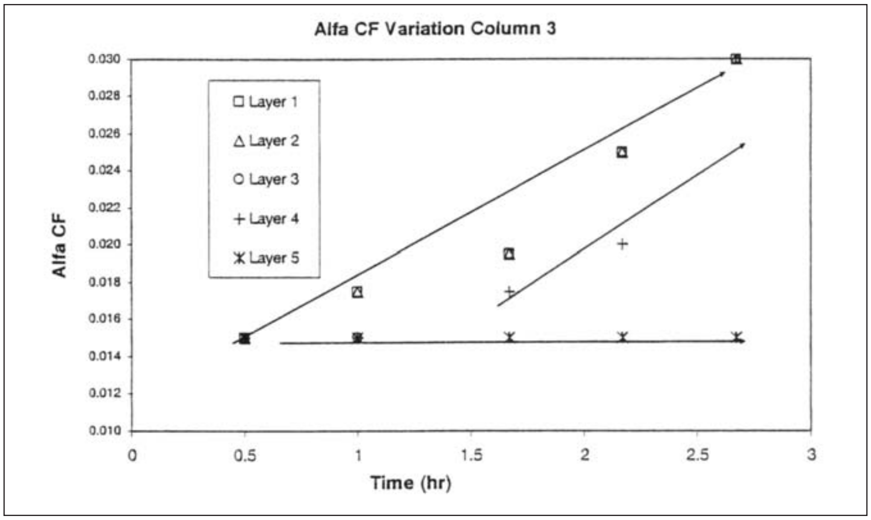

Figure 13. α_{cf} variation pattern observed in column 3 during the fitting process.

times, but varied almost linearly with a greater angular coefficient toward the end of the experiment. The observed behavior may indicate that this parameter is highly dependent on the amount of water available for absorption to the solid waste.

Although it was possible to mimic the experimental curves using the Richards equation, it became evident that the conceptual model used (Richards Equation) was not a physically sound representation of the observed phenomenon.

REFERENCES

1. D. G. Fenn, K. J. Hanney, and T. V. DeGeare, *Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites,* EPA/630/5W-168, U.S. EPA, Cincinnati, Ohio, 1975.
2. E. R. Perrier and A. C. Gibson, *Hydrologic Simulation on Solid Waste Disposal Sites,* EPA-SW-868, U.S. EPA, Cincinnati, Ohio, 1980.
3. J. R. Gee, *Prediction of Leachate Accumulation in Sanitary Landfills,* Proceedings of the 4th, 5th, 6th Annual Madison Conference of Applied Research and Practice on Municipal and Municipal and Industrial Waste, 1981, 1982, 1983.
4. P. R. Schroeder, P. A. Dozier, P. A. Zappi, B. M. McEnroe, J. W. Sjostrom, and R. L. Peyton, *The Hydrologic Evaluation of Landfill Performance (HELP) Model*—Engineering Documentation for Version 3, U.S. EPA Risk Reduction Laboratory, Cincinnatia, Ohio 45268, 1984.

5. W. A. Straub and D. R. Lynch, Models of Landfill Leaching: Moisture Flow and Inorganic Strength, *Journal of the Environmental Engineering Division, ASCE, 108:EE2, pp. 231-250, 1982.*
6. G. P. Korfiatis, A. C. Demetracopoulos, E. L. Dourodimos, and E. G. Nawy, Moisture Transport in a Solid Waste Column, *Journal of the Environmental Engineering, 110*:4, pp. 789-796, 1984.
7. A. C. Demetracopoulos, G. P. Korfiatis, E. L. Bourodimos, and E. G. Nawy, Unsaturated Flow through Solid Waste Landfills: Model and Sensitivity, *Water Resources Bulletin, 22*:4, pp. 601-609, August 1986.
8. J. J. Noble and A. E. Arnold, Experimental and Mathematical Modeling of Moisture Transport in Landfills, *Chemical Engineering Commission, 100,* pp. 95-111, 1991.
9. S. Ahmed, R. M. Khanbilvardi, J. Fillos, and P. J. Gleason, Two-Dimensional Leachate Estimation through Landfills, *Journal of Hydraulic Engineering, 118*:2, pp. 306-322, 1992.
10. R. M. Khanbilvardi, S. Ahmed, and P. J. Gleason, Flow Investigation for Landfill Leachate (FILL), *Journal of Environmental Engineering, 121*:1, pp. 45-57, 1992.
11. L. A. Richards, Capillary Conduction of Liquids through Porous Media, *Physics, 1,* pp. 318-333, 1931.
12. W. R. Gardner and M. S. Mayhugh, Solutions and Tests on the Diffusion Equation for the Movement of Water in Soil, *Proceedings, Soil Science Society of America, 22,* pp. 197-201, 1958.
13. I. Remson, G. M. Hornberger, and F. J. Molz, *Numerical Methods in Subsurface Hydrology,* Wiley Interscience, New York, 1971.
14. J. T. Rulon, R. Rodway, and R. A. Freeze, The Development of Multiple Seepage Faces on Layered Slopes, *Water Resources Research, 21*:11, pp. 1625-1636, 1985.
15. M. A. Celia, E. T. Bouloutas, and R. L. Zarba, *A General Mass-Conservative Numerical Solution for the Unsaturated Flow Equation, Water Resources Research, 26,* pp. 1483-1496, 1990.
16. J. Capelo, *Modelagem e Simulação do Fluxo Vertical de Umidade em Resíduos Sólidos Não Saturados* Doctor of Science dissertation, Department of Civil and Environmental Engineering, Federal University of Ceara, Brazil.
17. C. Zeiss and M. Uguccioni, Mechanisms and Patterns of Leachate Flow in Municipal Solid Waste Landfills, *Journal of Environmental Systems, 23*:3, pp. 247-270, 1994.
18. D. L. Nofziger, K. Rajender, S. K. e Su, Pei-Yao, *CHEMFLO–One-Dimensional Water and Chemical Movement in Unsaturated Soils,* Department of Agronomy, Oklahoma State University, Stillwater, Oklahoma 74078, U.S. Environmental Protection Agency–CR-812808.
19. R. H. Brooks and A. T. Corey, *Hydraulic Properties of Porous Media,* Hydrology Papers No. 3, Colorado State University, Fort Collins, Colorado, 1964.
20. Van Genuchten, M., A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, *Soil Science Society of America Journal, 44,* pp. 892-898, 1980.
21. C. S. Simmons, D. R. Nielsen, and J. W. Biggar, Scaling of Field-Measured Soil Water Properties,e *Hilgardia, 47,* pp. 77-173, 1979.

22. C. H. Benson and X. Wang, *Soil Water Characteristic Curves for Solid Waste,* Environmental Geotechnics Report 98-13, Environmental Geotechnics Program Department of Civil and Environmental Engineering University of Wisconsin–Madison, Madison, Wisconsin 53706, 1998.

Direct reprint requests to:

J. Capelo
Federal University of Ceara
Department of Civil and Environmental Engineering
Campus do Pici
Centro de Tecnologia Bloco 713
Terreo, CEP 60451-970
Fortaleza–Ceara, Brazil
e-mail: zecapelo@hotmail.com