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IMPACT OF THREE DIFFERENT HYDRAULIC CONDUCTIVITY EXPRESSIONS ON MODELING LEACHATE PRODUCTION IN LANDFILLS

O. OLAOSUN

H. R. BAHERI

University of Calgary, Alberta, Canada

ABSTRACT

Unsaturated flow in porous media, modeled by Richard's Equation, requires the identification of the moisture advective velocity in terms of hydraulic conductivities. In this study, the impacts of three hydraulic conductivity expressions on the ability of the unsaturated flow model to predict leachate production in landfills were investigated. The two power expressions (Power I and II) and PITTLEACH-2 hydraulic conductivity expression were used along with the Richard's Equation to estimate the leachate flow in solid wastes. Experimental data on leachate generation from eight laboratory scale cells were also used to assess the impact of different expressions on prediction of leachate flow. It was found that using PITTLEACH-2 hydraulic conductivity expression resulted in much better predictions of the leachate generation in all the eight cases studied here.

INTRODUCTION

Landfills are still an attractive waste disposal route. Landfilling of the wastes, however, has several limitations, the most important of which is the infiltration of rainwater into the refuse mass and the subsequent movement of leachate out of landfill and into the surrounding soil.

The volume of leachate produced in a municipal solid waste landfill is determined primarily by the amount of water percolating through the waste layers. It is also affected by the biodegradation and the mass transfer taking place in the landfill [1]. There are two principal approaches for prediction of leachate flow in landfills. In the water balance methods [2-5], the amount of water percolating through the solid waste is obtained by subtracting the runoff, change in waste moisture content, and evapotranspiration from total precipitation. In the computation of leachate flow by this method, the actual process of moisture movement through the refuse is not taken into consideration.

The other approach uses the classical theory of unsaturated flow through porous media to predict moisture flow in landfill [1, 6, 7]. Korfiatis [7] used the unsaturated flow theory to model the moisture transport through refuse material place in an experimental leaching column. The unsaturated flow theory was also used by Ahmed [6]; the two-dimension Richard's Equation was solved using a finite difference scheme. To model the heterogeneous nature of the waste, Olaosun [8] used the unsaturated flow model along with the multi-domain approach. The waste heterogeneity leads to flow channeling and contribute to earlier leachate breakthrough time. Central to the multi-domain approach is the assumption that the landfill medium can be considered as a number of distinct sections, each is treated as a homogeneous media with separate hydraulic properties. These properties are assumed distributed log normally and leachate flow in each of the sections is described with the Richard's Equation.

Models based on unsaturated flow in porous media require the identification of the moisture advective velocity in terms of hydraulic conductivities. In this study, the main objective was to assess the impact of the hydraulic conductivity expressions on modeling leachate production in landfills. Three different expressions have been used to model the variation of unsaturated hydraulic conductivity, $K(\theta)$, with the moisture content, θ, which was later used in modeling landfill leachate production. The multi-domain approach [8] was used to model the leachate generation, as it was essential to account for the waste heterogeneity and flow channeling.

UNSATURATED HYDRAULIC CONDUCTIVITY EXPRESSIONS

Several formulas relating the unsaturated hydraulic conductivity, $K(\theta)$, to moisture content, θ, and the saturated hydraulic conductivity, K_s, have been proposed in literature and employed in landfills modeling [5, 9-11]. Among the expressions is the Power expression I given as follows:

$$K(\theta) = K_s \left(\frac{\theta}{\theta_s} \right)^B \tag{1}$$

where,

θ_s = saturated moisture content, and

B = empirical coefficient, dependent on the medium size distribution

This equation is based on the assumption that flow of water in soil is controlled by the smaller of two pores in sequence. In addition, the pore radii and water content of the porous body was related using a moisture retention function and the capillary rise equation.

Schroeder et al. [5] and Charbeneau [10] used modified versions of the power expression (Power II), given as:

$$K(\theta) = K_s \left(\frac{\theta - \theta_f}{\theta_s - \theta_f} \right)^B \tag{2}$$

The equation implies that the value of $K(\theta)$ is effectively zero for θ less than or equal to the field capacity, θ_f. Schroeder et al. [4] (1994) used a value of $B = 12.5$ for municipal solid waste layers in the HELP model.

Al-Yousfi [1] proposed and verified a different expression for unsaturated hydraulic conductivity, PITTLEACH-2 expression:

$$\begin{aligned} &K(\theta) = K_s\ (\theta_f - \theta) = 0 \qquad for\, \theta \le \theta_f \\ &K(\theta) = K_s\ (\theta - \theta_f)\ln\left\{1 + \left[\exp\left(-1/\left(\theta - \theta_f\right)\right) - 1\right]\frac{\theta}{\theta_s}\right\} \qquad for\, \theta > \theta_f \end{aligned} \tag{3}$$

The expression was derived mathematically using the probability-based entropy concept. The equation simulates the unsaturated hydraulic conductivity as a dependent function of moisture of landfill media. Presumptions of a monotonous increase in $K(\theta)$ in correspondence to an increasing θ (from $\theta = 0$ to $\theta = \theta_s$) were made. It was further assumed that all values of θ between zero and saturation are equally likely. The expression does not have any empirical parameters.

The expression employed for the hydraulic diffusivity, $D(\theta)$ in this study is:

$$D(\theta) = \mathrm{K}(\theta)\frac{\psi_s}{\theta_s} b \left(\frac{\theta_s}{\theta} \right)^{B+1} \tag{4}$$

The above equation correlates $D(\theta)$ with hydraulic tension, ψ, and an empirical parameter, $b = 4$, as adopted from Korfiatis [7].

RESULTS

The variation of hydraulic conductivity with moisture content for each of the expressions is given in Figure 1. From Figure 1, it can be seen that the predictions of the unsaturated hydraulic conductivity from PITTLEACH-2 expression is generally higher than the other Power expressions. The moisture content thresholds of the unsaturated hydraulic conductivity are 22, 32, and 43 percent for the PITTLEACH-2 expression, Power expressions I, and Power expression II, respectively.

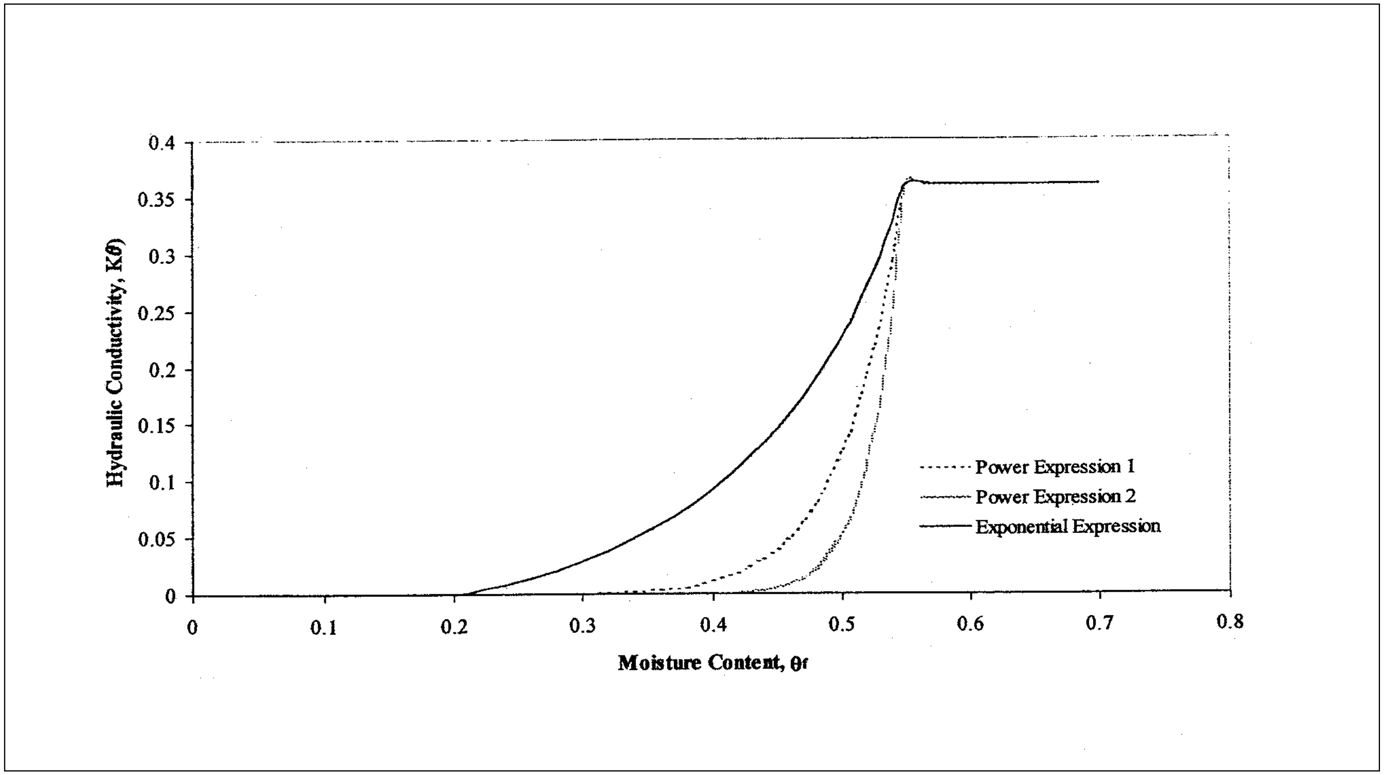

Figure 1. Variation of hydraulic conductivity with moisture content as estimated from the Power and PITTLEACH-2 Expressions for typical values of $K_s = 0.36$ m/hr, $\theta_s = 0.55$, and $\theta_f = 0.20$.

The above three expressions were used in the simulation of leachate production from eight laboratory scale cells. A summary of the eight cells parameters can be seen in Table 1.

The multi-domain approach used by Olaosun [8] was used to simulate the leachate flow from these lysimeters. The fact that the municipal solid waste is heterogeneous leads to the preferential flow of fluids. Thus, by dividing the waste domain into sections, where each section represents a narrower range of hydraulic properties, the multi-domain approach is able to simulate heterogeneity of the wastes and its contribution to the flow channeling.

Part of the simulation results for leachate generation by the three different hydraulic conductivity expressions are shown in Figures 2 through 5 and in Table 2. The results showed that the Power expressions I and II underestimated the total volume of leachate in all the cases studied here. The simulation results using Power expression II did not predict any leachate production in any cells. This was mainly due to the fact that the moisture content of the cells was below the threshold value of Power II expression of 43 percent during the tests. The expression predicted a zero unsaturated hydraulic conductivity and, therefore, no leachate flow. In other words, this expression allows for the storage of moisture within the waste matrix and the moisture storage is higher than the actual storage in the cells, thus no leachate production was predicted using this expression.

Table 1. Summary of the Parameters for the Eight Solid Waste Cells [7, 12]

Parameters	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Korfiatis cell
Average infiltration rate, cm/hr	3.75	5.33	4.00	3.08	1.71	1.38	2.92	3.08
Total infiltration, L	310	435	325	340	285	355	305	83.64
Total discharge, L	260	245	240	245	90	105	100	44.884
Cell density, kg/m^3								
Initial	323	420	458	267	353	445	432	88.6
Final	522	539	532	413	607	492	504	
Initial moisture content (vol/vol)	0.08	0.11	0.12	0.07	0.09	0.11	0.11	0.0986
Field capacity (vol/vol)	0.1014	0.1814	0.152	0.1072	0.1702	0.1979	0.186	0.20
Hydraulic conductivity, $cm/s \times 10^3$	10.2	9.7	14.0	8.4	0.12	0.076	6.9	12.7
Porosity (vol/vol)	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.55

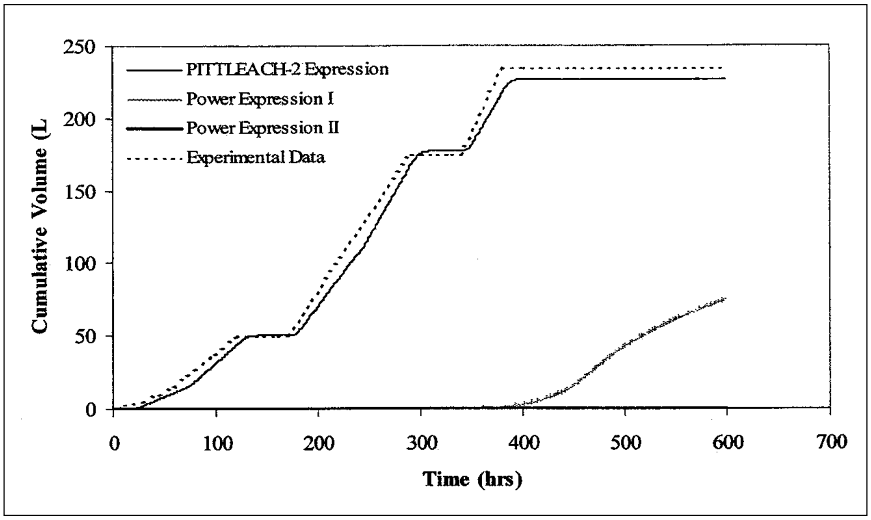

Figure 2. Comparison of theoretical and experimental leachate discharge for cell #2 using the Power I & II and PITTLEACH-2 Expressions (no leachate generation using Power II expression).

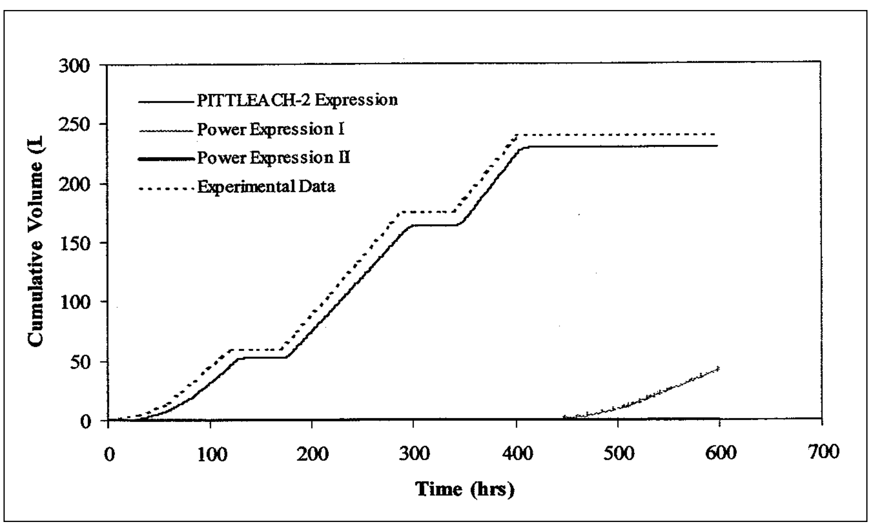

Figure 3. Comparison of theoretical and experimental leachate discharge for cell #3 using the Power I & II and PITTLEACH-2 Expressions (no leachate generation using Power II expression).

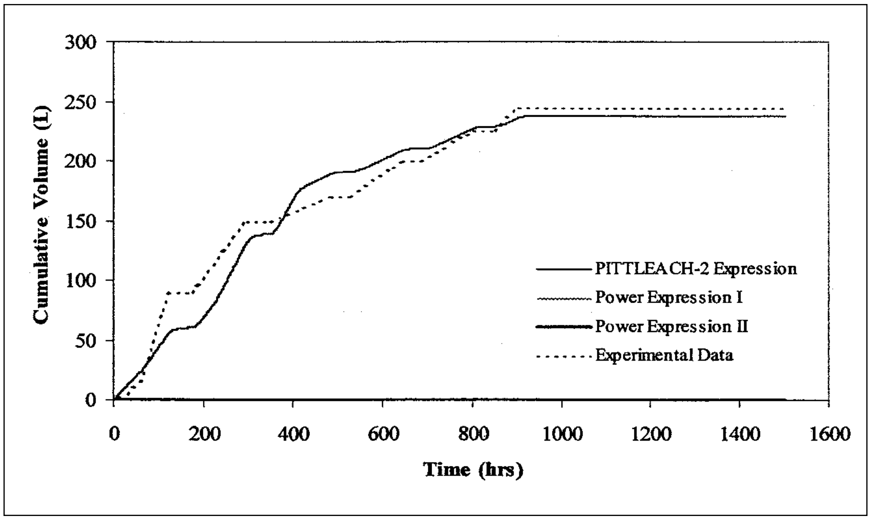

Figure 4. Comparison of theoretical and experimental leachate discharge for cell #4 using the Power I & II and PITTLEACH-2 Expressions (no leachate generation using Power II expression).

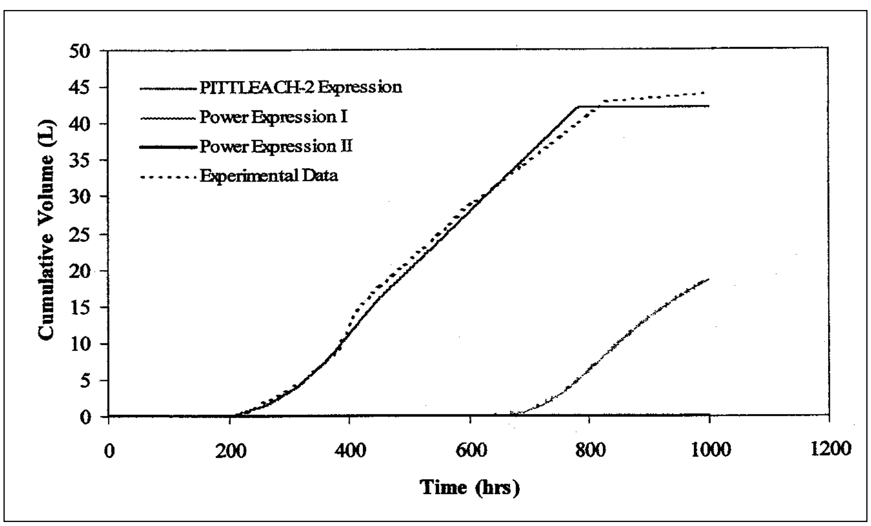

Figure 5. Comparison of theoretical and experimental leachate discharge for cell #5 using the Power I & II and PITTLEACH-2 Expressions (no leachate generation using Power II expression).

Table 2. Comparisons of the Average Errors in Predictions Using the Three Expressions (Average Error Based on 5 Points)

	Average error in leachate generation (%)		
Cell	PITTLEACH-2	Power I	Power II
1	7	> 100	> 100
2	6	92	> 100
3	15	95	> 100
4	12	> 100	> 100
5	23	> 100	> 100
6	42	> 100	> 100
7	21	> 100	> 100
Korfiatis	4	85	> 100

Note: > means greater than.

The performance of the Power expression I can be described by the same reasoning as above, but in the Power expression I, the threshold moisture content was about 32 percent, thus, leading to the production of some leachate in some of the cells with higher moisture content. The fact that the power expressions give lower unsaturated hydraulic conductivity than the PITTLEACH-2 expression for all moisture contents, leads also to slower moisture movement, and thus, higher breakthrough times, as can be seen in Figures 2 through 5.

CONCLUSION

From the results presented, it can be concluded that the empirical expressions used to model unsaturated hydraulic conductivity has a significant effect on the ability of the unsaturated flow model to predict the production of leachate in landfills. The PITTLEACH-2 expression resulted in better prediction of the leachate generation for the eight cells studied here. This was mainly due to the fact that the other two expressions had considerably higher moisture content thresholds.

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Direct reprint requests to:

O. Olaosun
Department of Chemical & Petroleum Engineering
University of Calgary
2500 University Drive
Calgary, AB, Canada T2N 1N4