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# Two Domain Flow Method for Leachate Prediction Through Municipal Solid Waste Layers in Al–Amari Landfill Site

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## Abstract

Existing leachate models over–or underestimates leachate generation by up to three orders of magnitude. Practical experiments show that channeled flow in waste leads to rapid discharge of large leachate volumes and heterogeneous moisture distribution. In order to more accurately predict leachate generation, leachate models must be improved. To predict moisture movement through waste, the two–domain PREFLO, are tested. Experimental waste and leachate flow values are compared with model predictions. When calibrated with experimental parameters, the PREFLO provides estimates of breakthrough time. In the short term, field capacity has to be reduced to 0.12 and effective storage and hydraulic conductivity of the waste must be increased to 0.12 and effective storage and hydraulic conductivity of the wasted must be increased to 0.2 and 2.2 cm/s respectively. In the long term, a new modeling approach must be developed to adequately describe the moisture movement mechanisms.

***Keywords:*** Pollution Modeling; Ground Water Hydrology; Solid Waste Landfills; Leachate Generation; Two–Domain Flow.

## Introduction

Existing leachate prediction models over–or underestimates leachate generation by up to three orders of magnitude. Channeled flow in waste leads to rapid discharge of large leachate volumes and heterogeneous moisture distributions (Zeiss and Uguccioni, 1997). The objectives of this research are to evaluate two modeling approaches by, first, analyzing the theoretical bases of single domain water balance and two domain flow methods and determining the effects of channeling. Then, appropriate flow parameters are experimentally determined and leachate generation is predicted with a water balance and two–domain model using experimentally, calibrated parameters. the result are compared with measured values to evaluate the performance, determine deficiencies, and suggest the most appropriate short and long term modifications to predict leachate generation from municipal solid (MSW) layers.

## Percolation

PREFLO routes through the profile in two distinct ways depending on the domain. Moisture is conveyed through the matrix according to the Richards Equation (2) with sink terms for water removal by roots addition of water from channels, and removal or addition of water from boundaries.

$$\partial\theta t= \nabla (K(\Psi) \nabla (h))–R(h,z,t)+PF(h,z,t)–C(h,z,t) \qquad \ldots(1)$$

Moisture storage in matrix is implicitly determined from the $\Psi$-$\theta$-K relation ship used as in-out into the model because the matrix stores large amounts of moisture if high $\theta$ values correspond to high governing values for $\Psi$. For laminar flow through macropores, Poiseulle's Law (equation 2) is used as the governing equation.

$$Q_P = \pi \rho g r^4/8\mu \qquad \ldots(2)$$

In PREFLO, moisture is transferred laterally from the channels to the matrix according to Darcy's Law (Equation 1) by accounting for the head differences (Workman and Skaggs, 1990):

$$Q = \frac{2\pi r z_j K(h_{i,j})(H_P - k_{i,j})}{x_P} \qquad \ldots(3)$$

## Leachate Flow in Solid Waste Layers

Channeled flow is defined as the constricted flow through a fraction of the waste columns cross-section at higher velocities than are valid for Darcian flow (Zeiss and major, 1993). Thus, while Darcian flow is laminar and controlled by viscous forces, channeled flow may be laminar or turbulent and is dominated by the higher flow velocities. Darcian flow is only valid at Reynolds numbers between 1 and 10 (Bouwer, 1978; Bear, 1972). If the Reynolds number is above 10, as calculated from experimental date (Uguccioni, 1995), Darcys Law is not valid.

Leachate flow through MSW occurs in narrow channels and unlike Darcian flow in a homogeneous matrix, results in an irregular moisture front (Korfiatis et al., 1984; Noble and Arnold, 1991; Roberson et al., 1991). Channeling was significant in pilot scale tests (Uguccioni, 1995; Zeiss and Uguccioni, 1997). In this study, moisture movement is characterized by four parameters including (1) breakthrough time, (2) time to steady state or effective storage, (3) leachate volume, and affects leachate collection and treatment system design.

## Experimental Methods

The experiments were designed to accomplish three research objectives: (a) to confirm channeling, (b) to characterize key flow parameters in pilot scale cells such as practical field capacity FC p, pore size distribution index, effective storage ES, hydraulic conductivity $K_{us}$, breakthrough time $t_{bt}$, time to effective storage $t_{\mathbf{ES}}$, cumulative discharge V.

Al–Amari landfill located at 20 km northeast of Baghdad receive 10000–1200 ton/day of solid waste and its consists of a number of cells (around 21) a pilot model were adopted to simulate the cell in the landfill by using the same solid waste composition.

A $2^2$ factorial design was used in this study to allow for a range of simulation conditions. The two experimental factors were infiltration rate (equal to the precipitation rate because moisture was not allowed to runoff or evaporate) and low level. The high infiltration level was 18 to 25 mm/hr., corresponding to a 10 to 15yr. – 1hr. (according to Baghdad mayority/solid waste department records). Storm event, while the low level of 7 to 15 mm/hr. corresponded to a 2 yr. The high density cells were compacted to 600 kg/m$^3$, corresponding to well compacted landfills. The low density cells were compacted to approximated was 300 kg/m$^3$, corresponding with poorly compacted landfills. The experiment was performed in pilot scale cells with dimensions of 1.8 m length by 1.6 m width by 1.5 m height to minimize wall effects. Typical residential waste from Baghdad city was used, and average channel diameters were determined through supplementary key flow parameters were measured or calculated as follows: (1) practical field capacity, $FC_p$, was calculated by performing a mass balance of water from initial moisture content and infiltration. (2) Pore size distribution index, was derived from the published values for similar wastes (Schroeder et al., 1994 Zeiss and Uguccioni, 1995). (3) Effective storage, ES, was determined from the water balance when the discharge volume reached the infiltration volume. (4) the apparent bulk hydraulic conductivity, $K_{us}$, was calculated using breakthrough time , waste layer thickness, and $FC_p$, (5) breakthrough time, $t_{bt}$, was measured, as the time between first infiltration and the appearance of the first leachate discharge. (6) Time to effective storage, $t_{es}$, was estimated from the time of first infiltration to the time when the discharge equaled the infiltration rate. (7) The cumulative discharge, V, was estimated on a daily basis from the volume of leachate discharged. (8) Leachate event, $t_Q$, was measured as the time between the beginning of leachate discharge (>5ml/day) until flow decreased to less than 5 ml/day. The prediction of leachate flow variables $t_{tb}$, V, and PREFLO default parameters as a basis for comparison. The flow parameter values were then determined.

From the experiments and used as model inputs. Calibrated model runs with experimental values were compared with test and default results. The comparison of predicted to measured values was used to identify model deficiencies and possible improvements.

## Experimental Results

Key flow results are listed in Table 1 and shown graphically in Figures 1 through 4. The waste and flow parameters generally confirm the presence of channeled flow on a pilot scale using representative unshredded municipal solid waste:

- Characteristic particle size averaged 7.3 cm with a standard error of 0.5 cm and was therefore similar to reported raw waste particle size and slope (Hasselriis, 1984).
- Average representative pore diameter was 1.9 cm with a range of 1.6 to 2.2 cm

- The mean of the practical field capacity, $FC_p$, was 0.12 with a standard error of 0.006 the average value is therefore similar to previous experimental value of 0.1 to 0.13.
- Average effective storage, ES, was 0.19 with a standard error of 0.02. This value is approximately 1.5 times the average practical field capacity.
- The resulting apparent unsaturated hydraulic conductivity, $K_{us}$ is between 7.6. 10-**5** cm/s and 1.4. 10-2 cm/s, with a mean of 7.3. 10-3 cm/s, or about the same range as previously reported value of 1.18. 10-5 cm/s to 4.46. 10-3 cm/s (Zeiss and Major, 1993). Specific values of $t_{bt}$ , $t_{es}$ , V, and $t_Q$ for each experimental cell are illustrated in Figures 1 and 2 .
- The average break through time ($t_{bt}$) of 559 minutes with a standard error of 371 minutes is still very close to previously determined is values. These results show that channeled flow is established in large cells as in the time from the beginning of infiltration events to the first discharge is likely to be short in full scale landfills.
- On average, the time to effective storage is 24 days with a standard error of 6.7 days. $t_{es}$ is significantly longer for low infiltration intensity cells at 18 to 54 days (see Figures 3 and 4).
- The cumulative discharges, V, from the cells represents the total leachate volume produced during the experiments (see Figures 1 through 4 and table 1). The values for the high infiltration rate cells range between 234 (Cell 4, Figure 2) and 339 L (Cell 2, Figure 1) with an average of 135 L The cumulative discharge of the low infiltration rate cells was lower and resulted in higher moisture by approximately 134 L per cell.
- The duration of the flow events, $t_Q$, from the beginning to the end of discharge is shorter for high infiltration and longer for low infiltration rates, reflecting the additional moisture storage in the low infiltration cells. The average values for this parameter was 35 days with a standard error of 7.7 days.

In summary, the experimental results for key flow parameters are consistent with previously measured values and confirm that channeled flow lowers practical field capacity, $FC_p$, and effective storage, ES, and increases apparent hydraulic conductivity $K_{us}$. The flow experiments show lower breakthrough times $t_{bt}$, and time to effective storage $t_{es}$, but higher leachate discharges (V) over shorter duration ($t_Q$) than flow through a homogeneous porous matrix.

## Model Results–Evaluation and Discussion

This section (1) summarizes the results (see also Table 3, Figures 1 through 4) and describes the methodology used to calibrate the models, and (2) describes the factors leading the results (model deficiencies).

PREFLO predictions were carried out with default values (see Table 2) and resulted in Zero leachate generation as shown by the horizontal discharge curves in Figures 1 through 4. The parameter values were then substituted with the experimental results as summarized in Table 2.

In order to calibrate the model to achieve better prediction of moisture storage was set to the measured effective storage (approximately 1.5 times the measured practical field capacity). For PREFLO, the hydraulic conductivity was set 1. $10^{-5}$ cm/s to force flow through the channels. This value also corresponds to the lowest observed apparent unsaturated hydraulic conductivity (7.6 $10^{-5}$ cm/s). The calibrated prediction results are compared with measured results and summarized below (see Table 3 and Figures 1 through 4).

## Breakthrough Time $t_{bt}$

Particularly for low Intensity simulations (averaging 225 to 234 percent of measured). In some cases, PREFLO predicted drainage before any was observed (Figure 1 Cell 2, and Figure 2 Cell 3 and 4). The model begins to route moisture through the matrix at the start of the simulation using the Richards equation. If the initial moisture content and hydraulic conductivity of the profile are great enough, water may saturate the bottom node of the profile and drainage will occur. However, after infiltration begins the model routes flow through both channels and matrix. This can be observed from Figures 1 and 2. Although small volumes of discharge occur prematurely (Cells 2, 3, and 4), the drained volume increases considerably when infiltration begins. In contrast, premature drainage may result from one domain models using the Richards equation, although these models would not predict a large increase in drainage volume immediately after infiltration because channels are not considered and moisture is routed through the matrix according to the hydraulic conductivity.

## Time to Effective Storage $t_{ES}$

Generally, time to effective storage is underestimated by PREFLO (Table 3).

Steady-state leachate discharge is not reached in high infiltration PREFLO simulation. This is because the drainage rate out of the profile is limited by the channel volume and the saturated hydraulic conductivity of the matrix. At low infiltration rats, however, PREFLO underestimates $t_{ES}$. In these cases, the high moisture content initially present in the cells combined with the amount infiltrating results in discharge volumes equal to infiltration, soon after moisture loading commenced.

## Cumulative Leachate Discharge Volume V

PREFLO accurately predicts the discharge volume during the initial stages of infiltration, for all high infiltration intensity simulation (Figure 1 and 2, Cells 1through 4). This shown that explicit modeling of channeling improves leachate volume predictions during infiltration events.

## Duration of the Leachate Flow Event $t_Q$

With PREFLO, leachate continues to be discharged long after moisture loading ceases and after the measured event has stopped. As a result, the total amount of leachate and the duration of the leachate event predicted by PREFLO are greater than the measured values. Overestimation of the leachate flow event could also occur in one domain models which share PREFLO's matrix drainage.

## Conclusions and Recommendations

The experimental waste and flow parameters confirmed channeled flow in pilot scale cells. The practical field capacity of the eight test cells. $FC_p$, averaged 0.12, while the average effective storage, ES, was 0.19. HELP flow conductivity averaged 7.3 .$10^{-3}$ cm/s, consistent with previous channeled flow experiments. The average channel diameter was 1.9 cm. Experimental values for breakthrough time, $t_{bt}$, time to effective storage, $t_{ES}$, cumulative leachate volume, V, and duration of the leachate event, $t_Q$, averaged 559 minutes, 24 days, 202 L and 35 days, respectively, for the test cells. And the following recommendation may consider:

1. Allow infiltration through both the matrix and channels regardless of infiltration; partitioning of flow between the matrix and the channels would be based on cross sectional area of the waste layer each domain occupies and the maximum hydraulic conductivity of the matrix layer. At precipitation rates less than matrix hydraulic conductivity, channels would only receive direct precipitation. However, at precipitation rates greater than the matrix hydraulic conductivity, channels would receive both direct precipitation and excess from the matrix.
2. Specify a separate and distinct practical field capacity for the channel areas and the matrix. The channel practical field capacity than the matrix. Moisture would be stored in both the matrix and the channels until the practical field capacity of each area is reached, after which drainage would begin (drainage would first begin from the channels due to the smaller storage capacity and then from the matrix).
3. Specify effective storage moisture content, ES, for the entire layer. This moisture content is greater than the practical field capacity to account for the redistribution from the channels to the matrix. Rate from the waste would occur at the effective storage moisture content (waste would not drain to steady state at moisture contents below effective storage).
4. Experimentally determine the hydraulic conductivity of the matrix to ensure that the matrix can discharge leachate quickly to reach effective storage.
5. Allow drainage from the waste to cease when the drainage field moisture content capacity of the waste is reached. Channeled flow would cease when precipitation stops and the channel volume drains to practical field capacity ($FC_p$ is the only available storage in the channels); however, the matrix with the additional storage would continue to drain until a drainage field capacity is reached. As discussed, this field capacity, but less than the effective storage.

Further experimentation is necessary to the necessary parameter values, such as matrix hydraulic conductivity, cross sectional area of matrix and channels, matrix and channeled practical field capacity, effective storage and drainage field capacity. Investigative experiments should be conducted in pilot scale cells (as with the experiments in this study) to obtain parameter values.

**Table 1**
**Pilot Cell Waste and Flow Parameter Results.**

| Parameter | Mean | Standard Deviation | Standard Error |
|---|---|---|---|
| Rosin Rammler Particle Size (cm) | 7.3 | 1.7 | 0.5 |
| Pore Diameter (cm) | 1.9 | 1.0 | 0.2 |
| Waste Height (cm) | 88 | 7.0 | 3.0 |
| Initial Moisture Content (-) | 0.1 | 0.02 | 0.007 |
| Particle Field Capacity (-) | 0.12 | 0.016 | 0.006 |
| Effective Storage (-) | 0.19 | 0.06 | 0.02 |
| Apparent Unsaturated Hydraulic Conductivity (cm/s) | $7.3\times10^{-3}$ | $4.9\times10^{-3}$ | $1.7\times10^{-3}$ |
| Breakthrough Time (min) | 559 | 1069 | 371 |
| Time to Effective Storage (days) | 24 | 19 | 6.7 |
| Total Leachate Discharge Volume (L) | 202 | 91.6 | 32.4 |
| Duration of Event (days) | 35 | 21.8 | 7.7 |

**Table 2**
**Default and Calibrated Flow Parameters for PREFLO Prediction of Leachate Generation.**

<table>
<tr><th>Flow Parameter</th><th>Default Value</th><th>Calibrated Value</th><th>Rationale</th></tr>
<tr><td>Layer Thickness (cm)</td><td colspan="2">Cell Specified (See Table 1)</td><td rowspan="2">These values were determined by the experimental design of the pilot cells and remained constant</td></tr>
<tr><td>Initial Moisture Content (-)</td><td colspan="2">Cell Specified (See Table 1)</td></tr>
<tr><td>Porosity (-)</td><td>0.67</td><td>0.52</td><td>Experimental porosity was repeatedly determined to be 0.52</td></tr>
<tr><td>Saturated Hydraulic Conductivity (cm/s)</td><td>1E-3</td><td>1E-5</td><td>This value, corresponding to the lowest apparent unsaturated hydraulic conductivity was used to force infiltration through the waste channels</td></tr>
<tr><td>Pore Size Distribution Index (-)</td><td>0.45</td><td>0.65</td><td>The experimentally determined value of 0.65 was substituted for the default value</td></tr>
<tr><td>Pore Area (percent)</td><td>2.0</td><td>2.0</td><td>The measured value for solid waste (based on the measured pore diameter of 1.9 cm) was applied</td></tr>
</table>

**Table 3**
**Summary of Predicted PREFLO Output Parameters Expressed as Percent of Measured.**

| Case | Breakthrough Time (percent of measured) | Time of Effective Storage (percent of measured) | Total Volume Discharged (percent of measured) | Duration of Event (percent of easured) |
|---|---|---|---|---|
| Low Infiltration Intensity<br>Low Compaction Cells<br>Average<br>(Range) | 225<br>50 - 400 | 72<br>56 - 87 | 218<br>118 – 318 | 175<br>147 – 203 |
| Low Infiltration Intensity<br>High Compaction Cells<br>Average<br>(Range) | 234<br>67 - 400 | 54<br>31 – 76 | 303<br>257 – 330 | 152<br>107 – 197 |
| High Infiltration Intensity<br>Low Compaction Cells<br>Average<br>(Range) | 0<br>-300 - 300 | NA*<br>--- | 83<br>75 – 90 | 391<br>382 – 400 |
| High Infiltration Intensity<br>High Compaction Cells<br>Average<br>(Range) | -850<br>-1200 - 500 | NA*<br>--- | 128<br>126 – 130 | 577<br>571 – 582 |
| All Simulation<br>Average<br>(Range) | -98<br>-1200 - 400 | 63<br>31 - 87 | 183<br>75 - 330 | 324<br>107 - 582 |

* Steady state was not reached in simulations marked NA.

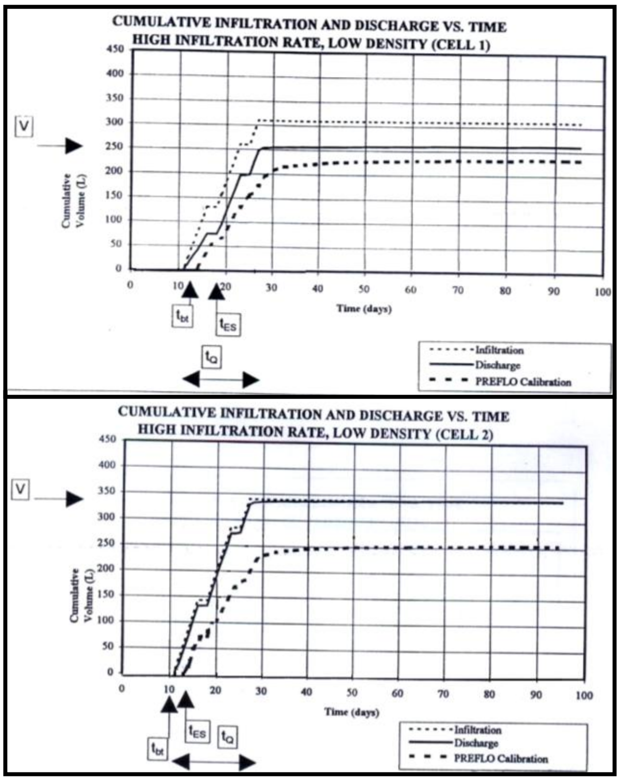


**Fig. 1. High Infiltration Rate, Low Density Results.**

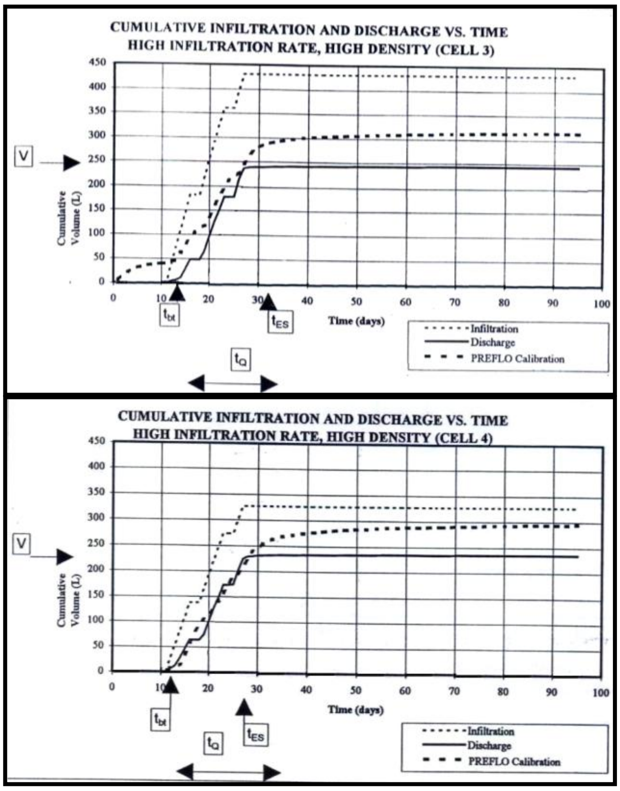


**Fig. 2. High Infiltration Rate, High Density Results.**

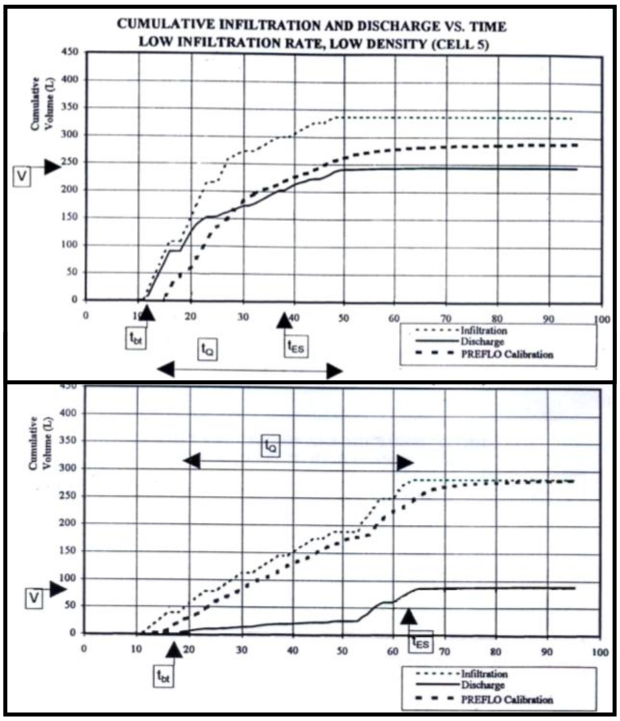


**Fig. 3. Low Infiltration Rate, Low Density Results.**

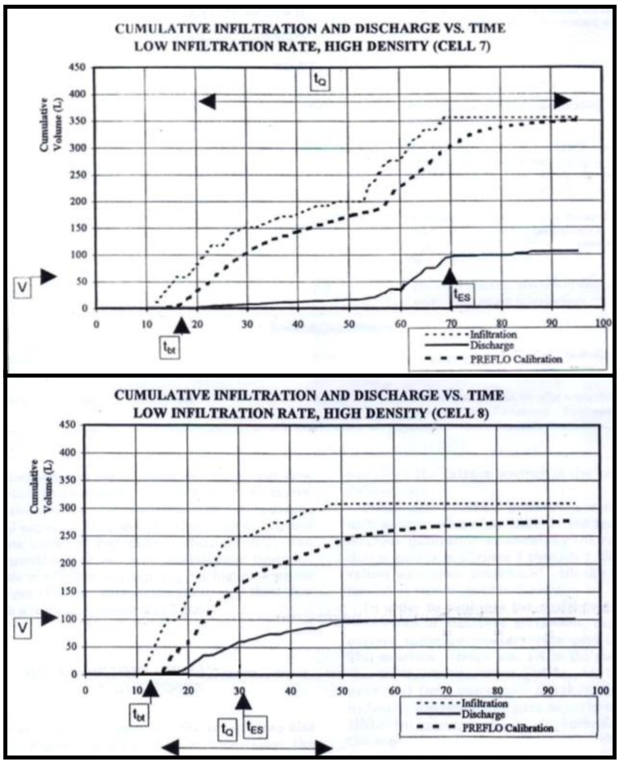


**Fig. 4. Low Infiltration Rate, High Density Results.**

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# حساب الراشح الناتج من طبقات النفايات الصلبة في موقع العماري بواسطة طريقة الجريان ضمن المجالين

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**الخلاصة**

يهدف البحث الى استخدام موديل PREFLO فيما يخص الراشح المتولد من النفايات الصلبة المتولدة في موقع العماري/ بغداد، ان النتائج العملية اظهرت ان الجريان القنوي لمادة الراشح ضمن النفايات الصلبة يؤدي الى تفريغ كميات كبيرة من هذه السوائل مع وجود توزيع عشوائي لمستويات الرطوبة (المحتوى المائي) ولغرض وضع صورة اكثر وضوحا ودقة لعملية تولد الراشح تم استخدام الموديل الرياضي ( PREFLO) وبمجالين ومن خلاله تمت مقارنة النتائج العملية والنظرية (للموديل) حيث تم التنبؤ واستنتاج زمن الاختراق breakthrough time وفي مستوى المديات القصيرة لوحظ حصول نقصان في السعة الحقلية بمقدار 0.12 وحصول زيادة في الموصلية الهيدروليكية وكذلك الخزن الفعال بمقدار 0.12 و2.2cm/sec اما في مديات التشغيل الطويلة فيجب الاعتماد على موديلات اخرى تقوم بتوصيف ميكانيكية حركة الرواشح.