ANALYSIS PROCEDURES FOR DESIGN OF LEACHATE RECIRCULATION SYSTEMS

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ABSTRACT
The purpose of this paper is to present a set of analysis procedures to design leachate recirculation systems. The analysis procedures presented are useful for designing leachate recirculation systems and developing operational procedures intended to maximize the benefits of recirculating leachate while avoiding potential detrimental effects from doing so. The following analyses are described in this paper: (i) evaluation of the effect of recirculating leachate on the hydraulic head on the liner; (ii) evaluation of the absorptive capacity of waste; and (iii) evaluation of leachate injection structure capacity. Previously published analysis procedures for selecting the spacing between injection structures are also presented. Based on the results of these analyses, the amount and frequency of leachate injection can be planned to make efficient use of the absorptive capacity of the waste mass and to avoid violating regulatory limitations regarding the hydraulic head on the liner.

INTRODUCTION

Controlled leachate recirculation (i.e., recirculation at lined facilities with leachate collection systems) has been utilized as a leachate management method at landfills in Europe and the United States since the 1980s (Reinhart, 1996). Extensive research efforts over the last two decades have shown that recirculation of landfill leachate into the refuse mass can accelerate waste stabilization, enhance gas production, and reduce the volume of leachate that must be treated compared to single-pass leaching operations. (Maier and Vasuki, 1996; Reinhart and Al-Yousfi, 1996).

Literature regarding leachate recirculation generally focuses on maximizing the rate of waste decomposition and depicts leachate recirculation as a continuous flow of liquid from top to bottom in a landfill, with the same liquid making numerous passes through the landfill. However, numerous landfill operators have found undesirable side effects from aggressive leachate recirculation such as leachate seeps, increased odors and interference with landfill operations (e.g., Maier et al., 1995; Reinhart, 1996). In addition, a recent slope stability failure at a landfill in Bogota, Colombia (El Tiempo, 1997) was partially caused by leachate recirculation. Therefore, many operators are now considering a less aggressive approach to leachate recirculation in order to obtain the benefits of the process while avoiding its potential problems.

In contrast to the typical multiple-pass paradigm for leachate recirculation, the less aggressive approach seeks to wet the waste mass uniformly without causing the development of pore pressures in large areas within the landfill (inevitably, localized pore pressures will exist where perched liquid is retained by low permeability waste or cover soil materials). The development of pore pressure leads to leachate seeps and reduces the factor of safety against slope instability. Because of the heterogeneous nature of waste, pore pressures can develop prior to saturation. Therefore, a conservative approach to leachate recirculation is to wet waste to approximately its field capacity moisture content (on average throughout the entire waste mass); that is, leachate is reinjected into the waste to the extent that the waste mass can absorb it without creating a potential for undesirable effects. At facilities where aggressive leachate recirculation is performed to maximize the rate of waste decomposition (i.e., bioreactor landfills), the author strongly recommends that pore pressure monitoring be performed and, that the presence of pore pressures be accounted for in slope stability analyses performed for these facilities.

The conservative approach could be referred to as the “one-and-a-half ” pass approach; the initial drainage of the leachate being the first pass and the reinjection of leachate that is then stored in the waste being the half pass. Note that the leachate storage capacity of a volume of waste will decrease over time because decomposition and compression will reduce the volume of voids within which the leachate is stored, and eventually stored leachate may be expelled.

Use of the one-and-a-half pass approach, is expected to minimize the development of pore pressures and, for many landfills, the net volume of leachate that must be treated and disposed of off-site will likely be reduced compared to single-pass leaching operation, even after considering leachate that may eventually be expelled due to waste compression. In addition, the increased moisture content throughout the waste mass due to the reinjection of leachate will result in enhanced gas generation, accelerated waste stabilization, and reduced post-closure maintenance costs, although perhaps not to the same degree that multiple-pass recirculation would cause. Unlike the multiple-pass approach, the one-and-a-half pass approach to leachate recirculation is not expected to significantly improve leachate quality compared to single-pass leaching operation.

Two of the three analysis procedures presented in this paper are applicable to both the multiple-pass and one-and-a-half pass approaches (i.e., evaluations of head on liner and injection structure capacity); the remaining analysis procedure (i.e., waste absorptive capacity analysis) is only relevant for the one-and-a-half pass approach). In the remainder of this paper, the following topics are addressed: (i) design and operational considerations regarding leachate recirculation; (ii) three analysis procedures useful for design of leachate recirculation systems; (iii) other useful design equations; and (iv) discussion and conclusions.

DESIGN AND OPERATIONAL CONSIDERATIONS

Considerations that affect the rate, frequency, and volume of leachate injection are: (i) the maximum allowable hydraulic head on the landfill liner; (ii) the leachate storage capacity of the waste and the development of pore pressures; and (iii) the rate at which leachate will percolate from the injection structures into the waste mass. Each of these factors is discussed in this section to provide a rationale for the analyses described in the following sections.

Hydraulic Head on Liner

State and Federal regulations require that the hydraulic head on a landfill liner be maintained below 12 in. (300 mm). Therefore, permitting a leachate recirculation system typically requires a demonstration that the proposed average leachate recirculation rate, in addition to precipitation, is not expected to cause a hydraulic head on the liner greater than 12 in. (300 mm).

Waste Absorptive Capacity and Pore Pressure Development

In areas of low to moderate precipitation, in-place waste typically is capable of absorbing and storing additional moisture, with faster filling rates generally resulting in dryer waste. That is, the moisture content of the waste is less than its field capacity, which is the maximum amount of moisture that can be retained by waste subjected to drainage by gravity. This potential to store additional moisture within the waste mass can be used to reduce the volume of leachate that must be treated and disposed of offsite. However, as reported by various landfill operators experienced with leachate recirculation, aggressive leachate recirculation can produce undesirable side effects. When the waste mass is saturated, gas extraction structures may not function due to excess liquid accumulation, leachate outbreaks tend to occur more frequently on sideslopes, and the factor of safety against slope instability is decreased. These undesirable effects can be linked to the development of pore pressures within the waste mass.

Injection Structure Capacity

The rate at which leachate can be injected into the waste mass should also be considered in the design of a leachate recirculation system. If sufficient injection capacity is not provided (e.g., too few injection structures), then the volume of reinjected leachate may be much less than the volume that the waste is able to absorb. On the other hand, if the injection capacity is much greater than the absorptive capacity of the waste, then the cost of constructing the system will be unnecessarily high or problems associated with long-term saturation of the waste may result.

Suggestions for addressing the factors listed in this section are presented in Table 1.

Limiting Factor	Design Considerations	Operational Considerations
The hydraulic head on the liner must be maintained below 12 in. (300 mm).	Perform HELP analysis to verify that the proposed average leachate recirculation rate (i.e., gallons per acre per day) in addition to precipitation is not expected to cause a hydraulic head on the liner greater than 12 in. (300 mm).	Limit the average leachate recirculation rate to the design rate used for the HELP analyses.
The development of pore pressure produces undesirable effects.	Design injection structures to provide uniform distribution of leachate throughout the waste mass. If appropriate, account for pore pressures when performing slope stability analyses.	Limit the total volume of leachate injected to that which, combined with moisture from other sources, would provide an average moisture content throughout the waste mass approximately equal to field capacity. Use of an injection structure should cease when the cumulative volume of leachate injected is sufficient to bring the waste in its influence zone to field capacity.
The rate at which leachate can be injected through any structure is finite.	Using the procedures presented in this paper, the injection capacity of each structure should be estimated and a sufficient number of structures should be provided to enable the injection of leachate at the design rate.	Adjust the actual frequency of leachate injection events based on actual percolation rates.

Table 1. Design and Operational Considerations

ANALYSIS PROCEDURES

Introduction

In this section, the following analysis procedures are presented for addressing the considerations discussed in the previous section: (i) evaluation of the effect of recirculating leachate on the hydraulic head on the liner; (ii) evaluation of the absorptive capacity of waste; and (iii) evaluation of leachate injection structure capacity.

Hydraulic Head on Liner

The evaluation of hydraulic head on the landfill liner is performed using the Hydrologic Evaluation of Landfill Performance (HELP) model. To simulate the effect of leachate recirculation on the hydraulic head acting on the landfill liner, the daily precipitation values used as input to the HELP model are increased by a constant value equal to the proposed average rate of leachate injection into the waste mass. This method enables precise control of the leachate recirculation rate being modeled; use of the leachate recirculation option included in HELP version 3, which only allows the recirculation rate to be specified as a percentage of leachate collected (Schroeder et al., 1994), does not allow a constant rate of leachate recirculation to be modeled. Using the method recommended in this paper, the value added to the daily precipitation data can be varied to estimate the maximum average rate at which leachate can be injected without causing a hydraulic head greater than 12 in. (300 mm). If the method of leachate recirculation used provides opportunities for evapotranspiration, then this effect should be accounted for in the analysis.

Note that HELP analyses are typically performed using the option of having the computer model calculate the initial waste moisture content based on steady-state conditions, and that this typically results in an initial waste moisture content near field capacity. As described in the next section, the actual in-situ moisture content of waste in many landfills is expected to be below field capacity. Therefore, for landfills where the waste is below field capacity, the results of the HELP analysis to simulate the effect of leachate recirculation represent conditions that would not exist until enough leachate is injected to raise the average waste moisture content above field capacity. If leachate injection is limited so that field capacity is not exceeded, then the results of the HELP analysis would be excepted to be conservative.

Reference	Description of Waste Sample or Sources of Data	Moisture Content (Note 1)	Field Capacity (fc) (Note 2)	Porosity (n) (Note 3)	Absorption Capacity
GeoSyntec and Todd, 1995	Samples obtained during drilling gas wells.	7 to 105%, 28% ave., by % of dry weight (30%, by vol. assuming total unit weight = 85 pcf)	46% ave., by vol. fc(% vol.) = -0.62*z*+54 (Note 4)	assuming G_s = 2.3 for waste, 49% ave. by volume n(%) = -0.046*z*+55 (Note 4)	16% ave., by vol.
McBean et al., 1995	Summary of field capacity and initial moisture contents of waste reported in the literature.	Initial moisture content: 4 to 21%, by vol., 15% ave., by vol.	28 to 40%, by vol. 33% ave., by vol.		10 to 29%, by vol. 18% ave., by vol.
Canziani and Cossu, 1989	Summary of some values of fc, and initial moisture content in the literature.	4 to 19%, by vol. 14% ave., by vol.	29 to 39%, by vol., for raw waste 35% ave., by vol.		19 to 25%, by vol. 21% ave., by vol.
Townsend et al., 1996	Alachua County Landfill leachate recirculation study; samples collected by augering.	moisture content before recirculation = 38.1 to 42.2, by % dry wt.; after recirculation = 45.6 to 84.2, by % dry wt.			
HELP Model, Version 3 (Schroeder et al., 1994)	Porosity, field capacity and wilting point based on the range of MSW water contents published by Tchobanoglous et al. (1977).		fc = 29.2% by vol.	n = 67.1%	

Table 2. Municipal Solid Waste Moisture Content, Field Capacity, and Porosity

Notes: vol. = volume
ave. = average
typ. = typical
fc = field capacity

1. The moisture content by percent of dry weight is the weight of liquids divided by the weight of solids times 100 percent. The moisture content by volume is the volume of liquids divided by the total volume.
2. The field capacity is the maximum moisture content that waste subjected to drainage by gravity can retain.
3. The porosity is the volume of voids divided by the total volume.
4. z = depth below landfill surface (ft).

Waste Absorptive Capacity

The absorptive capacity of waste is defined as the difference between its moisture content and its field capacity. Field capacity is defined as the maximum moisture content that waste subjected to drainage by gravity can retain. Representative values of waste moisture content, field capacity, and porosity found in the literature are presented in Table 2. The average absorptive capacities reported on Table 2 vary from 16 to 29 percent.

Injection Structure Capacity

Introduction: In this section, analysis procedures are presented for estimating the rate at which leachate can be introduced into a waste mass through two types of structures frequently used in leachate recirculation systems: (i) gravity-drained or pressurized horizontal trenches; and (ii) gravity-drained wells. Typical construction details for these structures are presented on Figures 1 and 2.

Gravity-drained conditions will exist in the injection structures shown on Figures 1 and 2 with the exception of the condition when leachate is injected through a forcemain and the leachate pumps are operated after the injection structures are filled; in this case a pressurized condition will exist. If desired, analysis of the pressurized condition could be performed by increasing the value of hydraulic head used in the following equations from hydrostatic head to pressure head. For the following discussion, it is assumed that leachate injection is performed by filling the injection trenches, allowing them to drain until nearly empty, and then filling them again.

Injection Trench Infiltration Rate: The infiltration rate from an injection trench is estimated by considering infiltration from the trench bottom and trench sides.

Infiltration Rate from Trench Bottom (q_b)

The infiltration rate from the trench bottom is estimated using the following equation (Bouwer, 1978).

$$q_b = k\left(1 + \frac{(h - P_o)}{z_f}\right) \quad (1)$$

where:

q_b = infiltration rate from bottom (length/time)
k = waste hydraulic conductivity (length/time)
h = hydraulic head on trench bottom (length)
P_o = waste suction (length)
z_f = depth of wetting front below trench (length)

Hence, the volumetric infiltration rate from the trench bottom per unit length of trench is calculated using the following equation.

$$\overline{Q}_b = q_b B \quad (2)$$

where:

$\overline{Q}_b$ = volumetric infiltration rate from trench bottom per unit length (length^3/(time · length))
B = trench width (length)

Infiltration Rate from Trench Sides (q_s)

The average head on a trench sidewall is one half the head on the bottom; therefore, the average infiltration rate from a trench sidewall (q_s) can be estimated using the following equation.

$$q_s = q_b / 2 \quad (3)$$

Hence, the volumetric infiltration rate from a sidewall of a trench per unit length ($\overline{Q}_s$) is:

$$\overline{Q}_s = q_s h \quad (4)$$

Using Equations (2) and (3) to eliminate q_s from Equation (4) gives:

$$\overline{Q}_s = \overline{Q}_b\left(\frac{h}{2B}\right) \quad (5)$$

Total Trench Volumetric Infiltration Rate ($\overline{Q}_t$)

The total volumetric infiltration rate is the sum of the infiltration rates from the trench bottom and both trench sides.

$$\overline{Q}_t = \overline{Q}_b + 2\overline{Q}_s = k\left(1 + \frac{(h - P_o)}{z_f}\right)(B + h) \quad (6)$$

Injection Well Capacity: The following simple approach to estimating injection well capacity is tentatively suggested. Multiplying Equation (6) by trench length (L) gives an expression for volumetric infiltration rate (Q_t) in units of volume per time.

$$Q_t = k\left(1+\frac{(h-P_o)}{z_f}\right)(B+h)(L) \qquad (7)$$

Equation (7) can be modified to estimate injection well volumetric infiltration rate (Q_w) by substituting well radius (r) for trench width (B) and half the circumference (πr) substituted for the length (L) of one trench sidewall.

$$Q_w = k\left(1+\frac{(h-P_o)}{z_f}\right)(r+h)(\pi r) \qquad (8)$$

where:

Q_w = volumetric infiltration rate from well (length^3/time)

Analysis Procedure: Some conservative simplifying assumptions can be made before applying the preceding equations to the calculation of the capacity of the injection structures. The waste suction (P_o), which is variable and difficult to quantify, is neglected; this assumption reduces the calculated infiltration rate. In addition, although the hydraulic head (h) and depth to wetting front (z_f) will vary as drainage from a trench or well progresses, if the depth to the wetting front is assumed to be constant, then only the variation of hydraulic head must be considered. The depth to wetting front can be assumed to be equal to: (i) the distance from the bottom of a well to the top of the leachate collection layer; or (ii) the vertical distance between groups of trenches. This assumed distance is effectively equal to the maximum distance to the wetting front and is representative of long-term steady-state conditions, for which the rate of infiltration is less than for initial conditions. Therefore, prior to waste saturation (i.e., when z_f reaches its maximum), the actual capacity of the injection structures is expected to be greater than the calculated capacity.

Using the assumptions listed above, the time required for an infiltration trench to drain can be calculated as follows. The time required for each infinitesimal volume of liquid ($d\overline{V}$) to drain from the trench is given by

$$dt = \frac{d\overline{V}}{\overline{Q}_t} \qquad (9)$$

Each infinitesimal volume can also be expressed as

$$d\overline{V} = n\,Bdh \qquad (10)$$

Substituting Equations (6) and (10) into Equation (9), and integrating from minimum hydraulic head (h_o) to maximum hydraulic head (h) gives the following expression for total drainage time (t).

$$t = \frac{n\,B\,z_f}{k(z_f - B)}\ln\left[\frac{(h+B)}{(h_o+B)}\frac{(h_o+z_f)}{(h+z_f)}\right] \qquad (11)$$

Similarly, Equation (8) can be used to solve for an expression for the time required for an injection well to drain.

OTHER USEFUL DESIGN EQUATIONS

The following design equations can be used to select the spacing between trenches and wells based on the calculated width or radius of waste that can be wetted by each type of injection structure.

The spacing of injection trenches operated under pressure can be calculated using the following equation (Al-Yousfi and Pohland, 1998).

$$E \le 2h\left(\frac{k_h}{k_v}\right)^{0.5} \qquad (13)$$

where:

E =horizontal distance between trenches (length)
h =hydraulic head in trench(length)
k_h = horizontal hydraulic conductivity (length/time)
k_v = vertical hydraulic conductivity (length/time)

Injection wells can be spaced at twice the radius of the zone of influence calculated using the following equation (Al-Yousfi and Pohland, 1998).

$$R = r\left(\frac{k_w}{k_r}\right) \qquad (14)$$

where:

R =radius of zone of influence (length)
r =radius of well (length)
k_w = hydraulic conductivity of well backfill material

(length/time)

k_r = hydraulic conductivity of refuse (length/time)

Note that k_r in Equation (14) is equivalent to k_h in Equation (13).

DISCUSSION AND CONCLUSIONS

The analysis procedures presented in this paper can be used to develop guidance regarding the layout of injection structures and the frequency of leachate injection. The number and spacing of injection structures can be varied to provide the leachate recirculation capacity needed based on the actual quantity of leachate that is generated. In some cases, it is theoretically possible for 100 percent of the leachate generated from a disposal facility to be injected into and absorbed by the waste mass. However, it is expected that some of the injected leachate will drain to the leachate collection system due to imperfect distribution of injected leachate, channelized flow of leachate within the waste, and the expulsion of liquid from waste due to compression.

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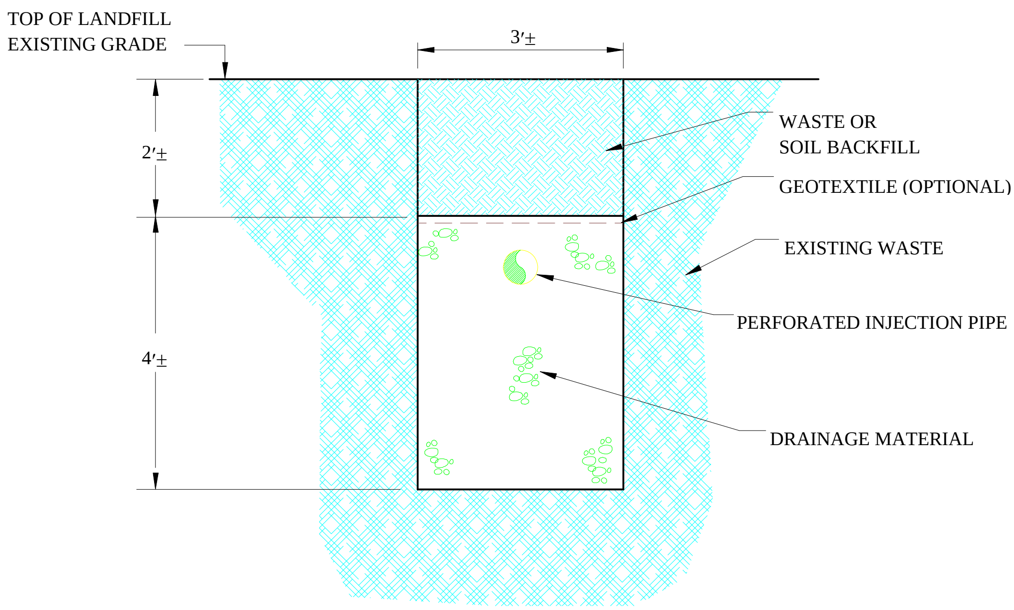

Figure 1. Typical Leachate Injection Trench

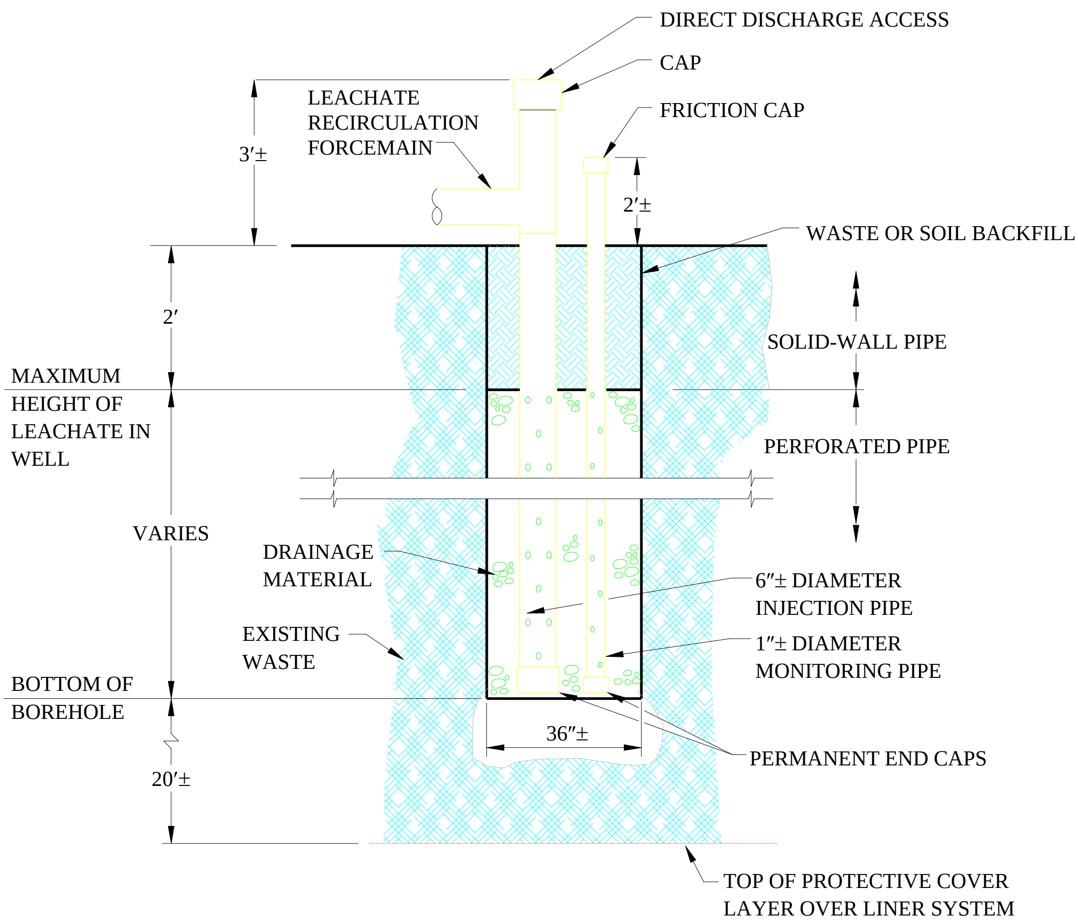

Figure 2. Typical Leachate Injection Well