

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Leachate Recirculation

The landfill waste mass is exposed to precipitation events including snow melts during the operational phase of the landfill life. Leachate is that portion of the precipitation which comes in contact with the waste. The precipitation that falls on the non-operational sections is usually collected separately and discharged as stormwater. If the stormwater and leachate come into contact at any time the entire mixture becomes leachate and must be treated as such.

During the operational phase of a landfill, a considerable volume of leachate will be collected. Historically, as the leachate was collected it was stored until a critical volume was reached when it was either treated and discharged on-site or transported for off-site treatment. Both of these options are expensive. Occasionally, the leachate collected from the landfill was recirculated to the landfill for storage and to provide evaporation opportunities. Recirculation achieves a decrease in the total volume of

leachate to be treated or disposed and a reduction in the degradable components of the leachate (Maloney, 1986).

Leachate recirculation is an attractive option not only due to the monetary concerns associated with disposal of the leachate but also because it decreases the liability associated with the closure of the landfill. Degradation of the organic fraction of the waste will occur during the early phases of the landfill's life while the liner is new and in its best possible condition rather than long into the future when the liner has aged and begun to deteriorate.

The in situ storage of leachate is possible because the water content of waste as it is received is generally well below the residual saturation of the waste. Researchers report the residual saturation to be between 20 and 35% by volume (Oweis et al., 1990; Korfiatis, 1984; Noble and Arnold, 1991). The residual saturation refers to the percent saturation above which fluid begins to flow by the driving force of gravity.

A typical landfill consists of several main components, a leachate collection system (LCS), lined sides, the contained waste mass including daily cover materials, and a final cap (Figure 2.1.1).

The LCS is the first component constructed and often consists of a low permeability material overlaid with a geomembrane to isolate (composite liner) leachate from the groundwater table. Perforated pipes, covered with a drainage and filter material, are placed over the geomembrane and connected to a sump in order to drain off the leachate as it collects on the liner. A more thorough discussion of the components and design of the LCS is provided in a later section.

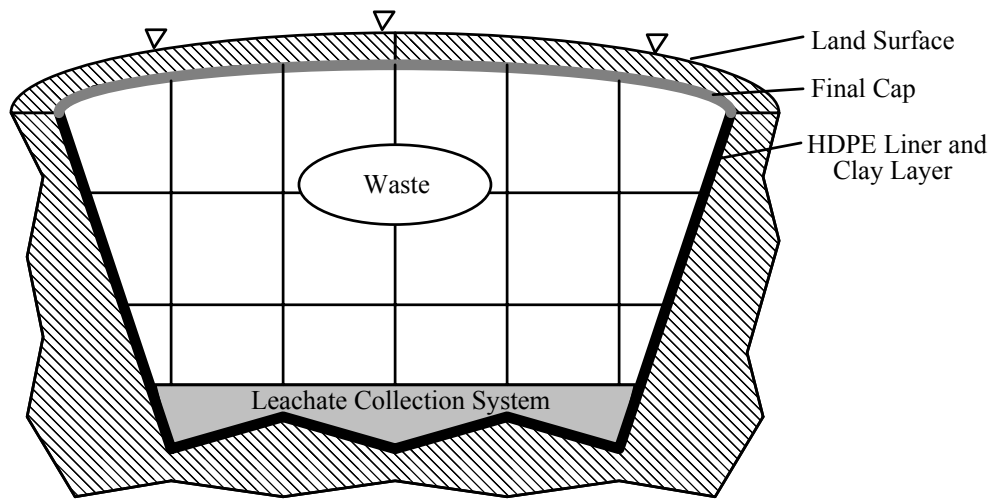


Figure 2.1.1. Typical below ground landfill cross-section.

Once the LCS has been constructed, waste can be placed. The first layer (lift) of waste is specially chosen to be free of materials which could compromise the LCS either by clogging the filter and drainage media or puncturing the geomembrane. Each lift of waste has to be covered with a material to limit access by insects, rodents, and wind blown litter. This material can be either a soil or any of a number of synthetic materials such as a spray-applied biodegradable foam.

The lined side slopes are constructed in one of two ways depending on the type of landfill being constructed. In an aboveground landfill design, the LCS is a pan on top of which the waste is piled in a pyramid fashion. During the filling operation, the side slopes are covered with daily cover materials. When a convenient time presents itself the

slopes are lined with another layer of soil, a geomembrane which is linked to the LCS geomembrane, top soil, and vegetation. In an excavation landfill design, the waste is placed into a depression, either natural or man made, in the ground. In this case, the side slopes are lined while the LCS is being constructed. The side slope geomembrane is attached to the LCS geomembrane and is covered with a single layer of soil to protect the liner from physical damage and exposure to the sun.

Once a landfill has been filled to capacity it receives a final cap. Presently, Subtitle D of the Resource Conservation and Recovery Act (RCRA) requires that the cap consist of an impervious high-density polyethylene (HDPE) liner covering the landfill to prevent further infiltration and then a layer of fill dirt and top soil. The landfill surface is usually seeded with grass to prevent erosion (Figure 2.1.1). Once closed, the standard procedure has been to drain the leachate from the landfill and remove it from the site.

This dry cell or "plastic tomb" approach to landfiling postpones the degradation of the organic mass within the landfill (Reinhart and al-Yousfi, 1996). Without moisture, the natural biological processes which stabilize the waste cannot take place. When moisture does enter the landfill, degradation will proceed and a contaminated leachate will be produced. Studies have shown that initially impervious liner systems are subject to deterioration (US EPA, 1988a/b and Miller, 1991b) and may leak even at the initiation of landfill operation (Lee and Jones-Lee, 1993). These factors combine to make the dry landfill a long-term environmental threat.

A wet cell approach has been shown to significantly reduce the stabilization time of the landfill mass and to potentially make the closed landfill less environmentally

threatening. Leachate and gas would be produced while the liner and collection system are new (Wall and Zeiss, 1995). Wetting has been accomplished either by a single pass of leachate through the landfill or multiple-pass leachate recirculation. A four-year study conducted in Sonoma County, California showed that the addition of clean water to the landfill will significantly reduce the strength and pollution character of the leachate generated. This decrease in leachate strength was attributed to dilution rather than enhanced biological activity (Leckie et al., 1979).

Numerous studies of the effects of leachate recirculation have shown increased biological activity (methanogenesis) and decomposition with increased moisture content (Barlaz et al., 1990). Some researchers have argued that the increased biological activity is stimulated by the movement of the moisture as much as by the increased moisture content (Klink and Ham, 1982). Studies have indicated that with leachate recirculation, the landfill can be stabilized in several years as compared to several decades associated with conventional operation (Pohland, 1975). Gurijala and Sulfito (1993) specified that a moisture content in the range of 50 to 60 % was best for methanogenesis and also indicated that the presence of sulfate tends to inhibit methanogenesis. Sulfate generally accounts for a small portion of MSW but may be leached from the gypsum in construction and demolition (C/D) materials in co-disposal situations.

It has been observed that leachate recirculation can result in an initial increase in the leachate organic strength (Miller and Townsend, 1995). This increase in the Chemical Oxygen Demand (COD) may be the result of enhanced hydrolysis of the refuse material. Another suggested approach was to recirculate leachate to closed cells operated

in parallel with active cells, as shown in Figure 2.1.2 (Doedens and Cord-Landwehr, 1989). The benefit of this procedure would be treatment of the leachate in the closed cells where an acclimated bacterial culture had been established and where the further hydrolysis of the refuse would be unlikely, resulting in a decrease in the overall leachate strength and a more rapid development of an acclimatized bacterial culture in the active cells.

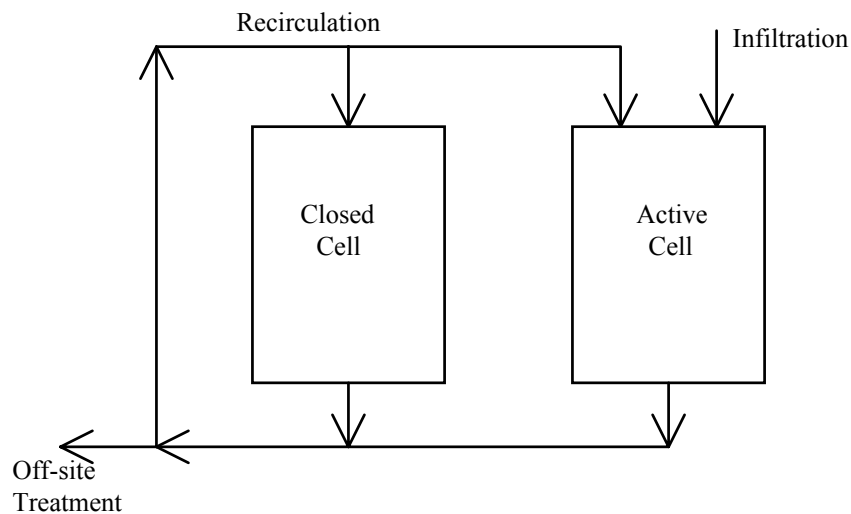


Figure 2.1.2. Leachate recirculation flow schematic.

Lema (1988) suggested that leachate recirculation can be used as the primary treatment method, followed by secondary treatment in order to polish the effluent prior to discharge. Leachate generated by the recirculation process has the potential to contaminate groundwater even though methane production may have stopped.

Pohland (1980) used lysimeters to study the effects of leachate recirculation. One lysimeter represented an open landfill cell which received precipitation, the second

lysimeter was sealed to prevent moisture loss by evaporation. The second lysimeter received tap water at the rate the first lysimeter received precipitation. After approximately one year, leachate was recycled to both lysimeters at equal flow rates. This study showed a decrease in leachate Total Organic Carbon (TOC), 5-day Biological Oxygen Demand (BOD<sub>5</sub>), and Chemical Oxygen Demand (COD) once recycle was implemented. While some of the decrease was attributed to dilution effects, a major factor was the enhanced biological activity within the lysimeter. This study also confirmed the decrease in waste stabilization time realized through leachate recirculation.

Pohland (1989) compared single pass of leachate to a continuous recycle (multi-pass) operation of a MSW landfill lysimeter. The recycle operation resulted in a decrease in degradable constituents (COD and Total Volatile Acids) but an increase in conservative elements (calcium, alkalinity, sodium) of the leachate as compared to the single-pass leachate.

Leachate recirculation has also been studied as a leachate treatment method. The cost of treatment by leachate recirculation has been shown to be much lower than any other on-site treatment method such as aerobic/anaerobic treatment processes, or lagoons (Lema, 1988 and Pohland, 1989).

Robinson and Maris (1985) conducted an 18-month leachate recirculation pilot study which showed a significant decrease in the recycled leachate BOD but high levels of COD, ammonia nitrogen, chloride, and some metals (specifically iron, manganese, sodium, and potassium) when compared to a parallel conventional system. They also conducted a full-scale study with a recycle operated cell and a control cell. Leachate was

applied by spraying and the landfill surface was furrowed to reduce leachate ponding. This study showed consistently lower and decreasing COD levels in the recycle area as compared to the control area where the COD remained essentially constant. A 40% reduction in COD was realized in 20 months. Ammonia and chloride concentrations did not decrease in either area. The study also revealed perching of leachate within the landfill. The leachate in the perched areas was found to be weaker than the leachate draining from the fill.

From these studies, the advantages of leachate recirculation have been clearly demonstrated, including:

- distribution of nutrients and enzymes
- pH buffering,
- dilution of inhibitory compounds,
- recycling and distribution of methanogens,
- leachate treatment,
- leachate storage, and
- evaporation opportunities.

In addition, the reuse of the land above a dry landfill is difficult due to the unstabilized character of the waste. Once water penetrates the landfill cover, the waste will begin to decompose. This biological activity will result in the settling of the landfill surface and the production of leachate; contamination of the surrounding groundwater



and soils may also ensue. In contrast, the waste in a wet landfill would be rapidly decomposed and stabilized, precluding long-term problems with groundwater contamination and enhancing land reuse opportunities.

The United States Environmental Protection Agency (EPA) has stated that recirculation is compatible with federal MSW regulations as long as Subtitle D regulations are not violated (US EPA, 1988b). Regulations from Subtitle D of RCRA require leachate recirculating landfills to have a composite liner. A composite liner (US EPA, 1988b) consists of an upper and a lower component. The lower component is a minimum of 3 ft of compacted soil with a conductivity less than  $10^{-7}$  cm/s. The upper component is a geomembrane which is in constant and uniform contact with the compacted soil. RCRA regulations limit the volumetric head on the liner to 30 cm (12 in.) in order to minimize the hydraulic gradient through the clay layer in the event of a rupture of the geomembrane. However, the practice of leachate recirculation has not been approved in all states (Reinhart, 1993).

### 2.1.1 Recirculation Methodologies

While lysimeter and laboratory studies have proven the benefits of leachate recirculation, full-scale implementation has proven challenging. In order to gain these biological benefits it is necessary to maximize the landfill volume exposed to leachate

movement. Several techniques have been used to apply leachate to the landfill. They are:

- Spray Infiltrators
- Surface ponds
- Horizontal recirculation trenches, and
- Vertical infiltration wells.

In addition, prewetting of the waste with a firehose as it is placed in the landfill is occasionally practiced. Each of the techniques has specific benefits and disadvantages associated with it.

#### 2.1.1.1 Spray Infiltrators

Spray application utilizes standard lawn sprinklers, surface infiltrators, and truck sprayers to apply moisture to lifts as they are being constructed. A truck sprayer consists of a tanker truck with a perforated spray bar attached transversely across the rear through which the leachate is distributed (Monroe County, 1993). The truck is driven across the landfill surface in overlapping strips.

The lawn sprinklers and surface infiltrators are generally constructed of a semi-rigid polyvinyl chloride (PVC) framework which can be easily moved in order to place

waste or to "wet" a different area. The spray aerator has lawn sprinklers attached to the PVC framework which distribute the leachate. The surface infiltrator has perforations in the PVC framework which distribute the leachate. The framework can be installed either holes up or down depending on wind conditions. This type of application increases evaporation opportunities for the leachate which results in both a decrease in leachate volume and the volatilization of low molecular weight organics. The problems associated with this method are

- clogging of the application device,
- odor,
- stormwater contamination,
- formation of hard-pan deposits which limit infiltration, and
- incompatibility with final closure.

The latter three concerns are the most serious. The hard pan deposits have been described as an almost impervious layer on the landfill surface which prevents the infiltration of leachate and causes localized ponding (Robinson and Maris, 1985).

Stormwater contamination is very serious since any volume of stormwater which comes in contact with leachate must, by federal and state regulations, be treated as leachate.

This contamination can result in significant increases in the leachate volume which must be managed. In most states, leachate must be treated prior to application to a closed landfill surface. Cureton et al. (1991) studied the effect of leachate application through a

vegetative cover. The study focused on the effect of leachate on the vegetative vigor of four plant species. Of the four species studied, none suffered serious toxic effects due to leachate recirculation. It was shown that leachate may need to be supplemented with a potassium fertilizer but contained sufficient levels of nitrogen and phosphorous to satisfy the nutrient requirements of most plant species. Mild iron toxicity was noted in one of the species studied. Canary reed grass performed the best of all species studied.

Daily application rates reported were 744 lpd/m<sup>2</sup> (18.3 gpd/ft<sup>2</sup>) of landfill surface with intermittent operation at a Delaware landfill (Watson, 1993) and 1.0 to 3.2 lpd/m<sup>2</sup> (0.025 to 0.078 gpd/ft<sup>2</sup>) of landfill surface in a United Kingdom study (Robinson and Maris, 1985).

### 2.1.1.2 Leachate Ponds

Leachate ponds have been used to recirculate leachate at several sites. This method consists of excavating a hole in the surface of the landfill which is then filled with leachate. The problems associated with this technique are:

- not applicable to northern climates where the leachate pond may freeze,
- renders portions of the landfill unusable,
- floating wastes,
- limited influence area,
- collects stormwater, and
- incompatibility with final cover requirements.

Townsend et al. (1995) documented studies on four leachate ponds operated at the Alachua County Landfill located near Gainesville, Florida. The infiltration rates from the ponds were determined based on mass balances about the ponds. Infiltration rates of  $6 \times 10^{-6}$  to  $1.9 \times 10^{-5}$  cm/s were reported. A total of 36,474 m<sup>3</sup> of leachate (63% of the leachate generated) was recycled through the ponds over a 28-month period. The ponds were consistently troubled with floating waste matter. One section of the pond was lined with chain-link fence material in an effort to mitigate the problem, however, this provided no significant improvement. The researchers concluded that, due to low

infiltration rates, ponds were viable primarily as an interim method to store excess leachate and should be used only in conjunction with other recirculation techniques.

Essentially, the use of leachate ponds is limited to providing extra on-site storage and interim leachate recirculation during the operational phase of the landfill life (Miller et al., 1993 and Watson, 1993).

#### 2.1.1.3 Horizontal Infiltration Trenches

Horizontal infiltration trenches consist of perforated PVC pipes surrounded by gravel or tire chips and are usually capped with a flow barrier such as an infiltrator or low permeability clay as can be seen in Figures 2.1.3 and 2.1.4. The migration of the gravel/tire chips is often prevented by either a thin layer of sand or by wrapping the entire trench with a geotextile (Monroe County, 1993). The pipe is centered horizontally within the trench and is placed at the bottom or the center of the trench. The trenches can be located either at the surface of the landfill or within each landfill lift. They can be operated either by gravity feed or under pressure.

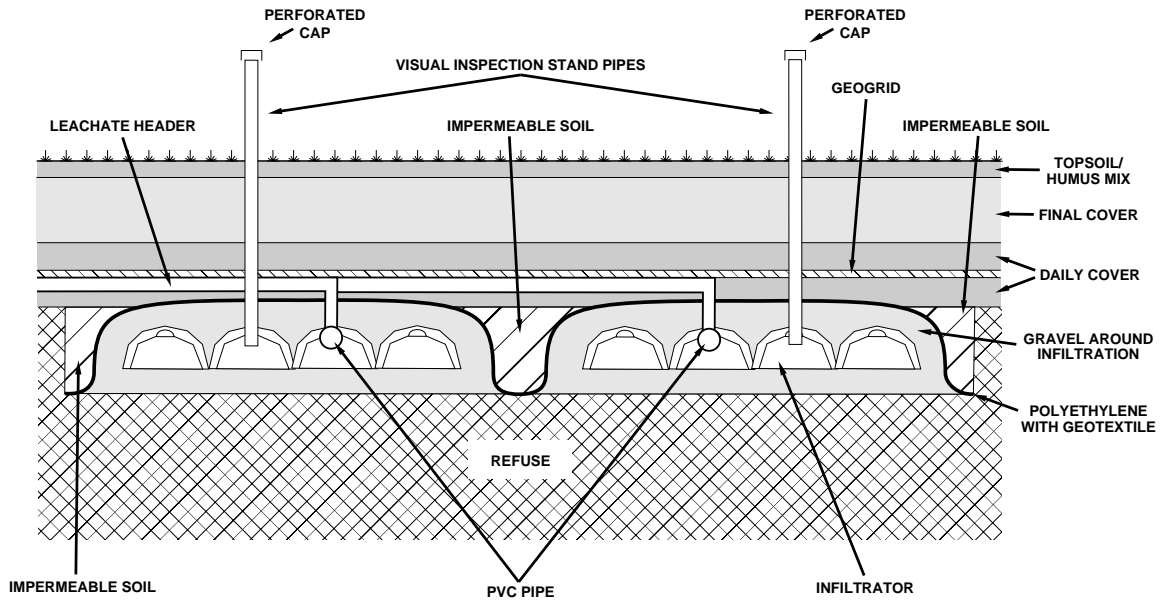


Figure 2.1.3. Horizontal leachate recirculation leach field.

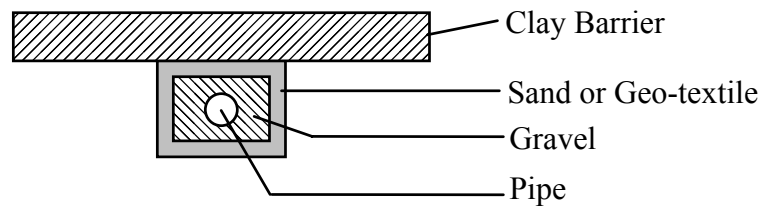


Figure 2.1.4. Horizontal leachate infiltration trench.

Studies have shown that head loss is not a limiting factor in the distribution of leachate through trenches (Townsend et al., 1994). However, the pressurized feed of leachate may require additional pumping power over that typically provided by a conventional leachate sump pump. If a large amount of settlement is anticipated, feed via

a flexible hose may prevent fracturing of the injection line. Pressurized operation may result in artesian conditions and increases the likelihood of leachate breakout. If pressurized operation is intended the trenches must be located at a safe distance from the landfill sides and top. The problems associated with trench infiltrators are:

- freezing,
- clogging,
- surface and side slope leachate seeps,
- limited recharge areas, and
- system failure due to landfill subsidence.

These problems can generally be addressed in the landfill design once the operational characteristics are defined. Also, the trench infiltrator is compatible with final closure requirements. Daily recirculation rates reported are 370 to 620 lpd/m of trench (30 to 50 gpd/ft) (Miller et al., 1993).

Al-Yousfi (1992) developed an equation which can be used to estimate the required horizontal distance between trenches. Equation 2.1.1 was based on the pipe perforation spacing, delivery head, and hydraulic conductivity.



$$E \leq 2h \quad (2.1.1)$$

where:

$$\begin{aligned} E &= \text{spacing between trenches, L} \\ h &= \text{delivery head of leachate, L} \end{aligned}$$

Townsend (1995) developed equations based on uniform flow theory for saturated conditions to estimate the area influenced by a horizontal infiltration trench. Equations for both isotropic (Equation 2.1.2) and an-isotropic (Equation 2.1.3) conditions were developed.

$$\frac{x}{y} = \tan\left(\frac{2\pi kx}{q}\right) \quad (2.1.2a)$$

$$Y_{\max} = \frac{q}{2\pi k} \quad (2.1.2b)$$

$$x_{\max} = \frac{q}{2k} \quad (2.1.2c)$$

$$x_{\text{well}} = \frac{q}{4k} \quad (2.1.2d)$$

$$x = \frac{q}{2\pi k_y} \tan^{-1}\left(\frac{x}{y} \sqrt{\frac{k_y}{k_x}}\right) \quad (2.1.3a)$$

$$Y_{\max} = \frac{q}{2\pi \sqrt{k_x k_y}} \quad (2.1.3b)$$

$$x_{\max} = \frac{q}{2k_y} \quad (2.1.3c)$$

$$x_{\text{well}} = \frac{q}{4k_y} \quad (2.1.3d)$$

where:

- $Y_{\max}$  = maximum upward impact of line source, L
- $q$  = leachate injection rate,  $L^2T^{-1}$
- $k$  = average waste permeability,  $LT^{-1}$
- $k_x$  = horizontal waste permeability,  $LT^{-1}$
- $k_y$  = vertical waste permeability,  $LT^{-1}$
- $x$  = horizontal distance from the line source, L
- $y$  = vertical distance from the line source, L
- $x_{\max}$  = maximum impact of line source, L
- $x_{\text{well}}$  = impact of line source at  $y=0$ , L

Equations 2.1.2 and 2.1.3 represent the outer limit of the flow path of liquid discharged from a horizontal line source in a saturated flow field, see Figure 2.1.5. However, the landfill is typically unsaturated. Permeability is at its maximum in saturated conditions and declines with decreases in the saturation. Therefore, the applicability of Equations 2.1.2 and 2.1.3 is questionable due to the variation in permeabilities encountered in the unsaturated environment and heterogeneities in the waste mass.

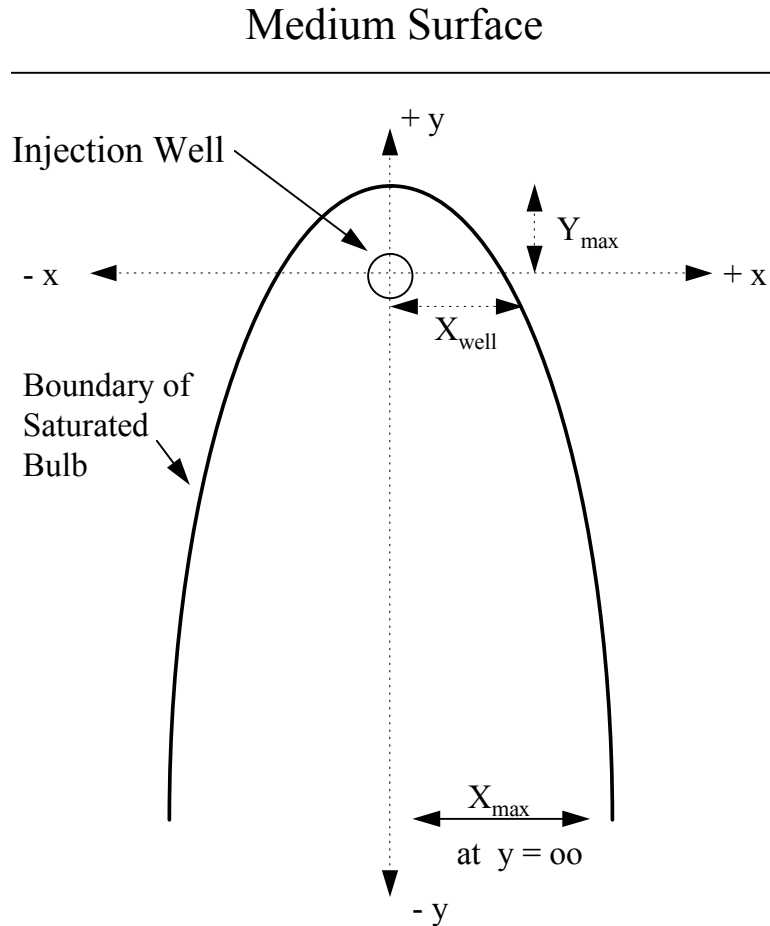


Figure 2.1.5. Saturated flow zone surrounding a horizontal injection well flow system under steady conditions.

Miller et al. (1991a) detailed the results of a landfill excavation study at the Central Solid Waste Management Center, Delaware. An influence distance of 6 m (20 ft) can be estimated based on saturated lenses encountered during the excavation procedure. Recirculation rates ranged from 110 to 18,600 m<sup>3</sup> (30,000 to 4,926,000 gal) per year for the years of 1983-1992 (Watson, 1993). Saturated lenses encountered during the excavation indicated that the daily cover material used was severely impeding moisture

movement within the fill. Once the cover material was punctured, the lenses drained quickly.

#### 2.1.1.4 Vertical Infiltration Wells

Vertical infiltration wells are typically constructed from a series of perforated manhole sections placed on top of each other as seen in Figure 2.1.6 (Kilmer, 1991 and Watson, 1993). The bottom section is generally not perforated. The perforated sections rise to just below the final elevation of the landfill. A solid section is then added to bring the well above the final grade. The entire structure is placed on a concrete pad for stability and is filled with gravel. The manhole sections are commonly 60 cm or 120 cm (2 or 4 ft) in diameter. Leachate is applied by filling the structure from the top with a portable hose, tanker, or permanent piping. Some designs have included the use of flow barriers within the structure (Figure 2.1.6). Each vertical section

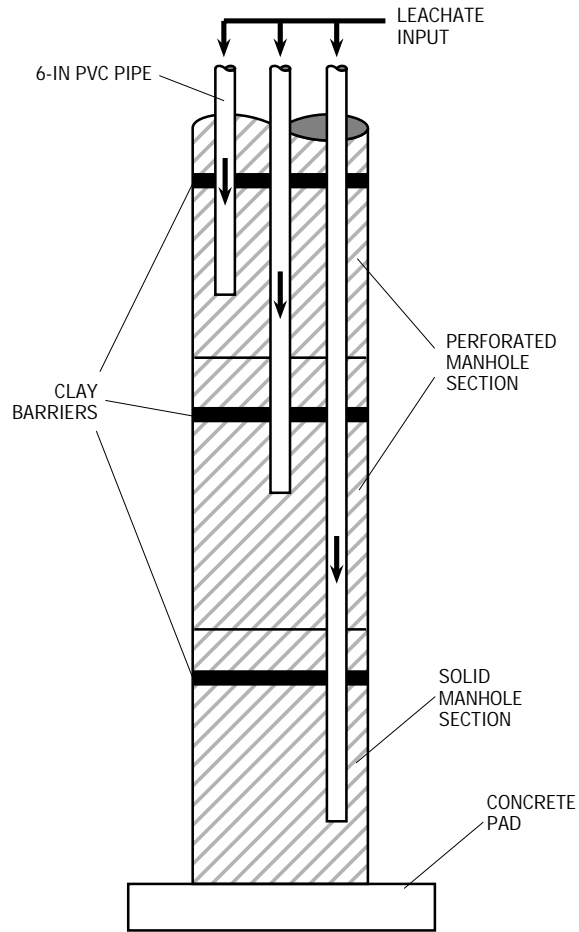


Figure 2.1.6. Sectionalized vertical leachate recirculation well.

is filled individually via separate pipes. The problems associated with the vertical infiltrators are similar to those of the horizontal trenches:

- surface and side slope leachate seeps,
- limited recharge areas,
- system failure due to landfill subsidence, and

- damage to the liner.

The vertical infiltration wells are compatible with final closure requirements. Daily recirculation rates reported are 8.2 to 94 lpd/m<sup>2</sup> (0.2 to 2.3 gpd/ft<sup>2</sup>) landfill at a Delaware landfill (Watson, 1993) and 67 lpd/m<sup>2</sup> (1.65 gpd/ft<sup>2</sup>) at the Owens-Corning Landfill (Merrit, 1992). The Delaware landfill used 1.2-m (4 ft.) diameter wells and pumps rated from 80 to 760 lpm (20 to 200 gpm). These wells were operated in a fill and drain manner. The Owens-Corning landfill used 70-cm (2.5-ft) diameter wells and leachate was applied at 5,450 to 13,600 lpd per well (1,440 to 3600 gpd).

Al-Yousfi (1992) proposed that the influence radius of a well could be estimated based on a mass balance of the leachate. Inflow from the well side area must be equal to the outflow from the zone of influence. Combining this concept with Darcy's Law resulted in Equation 2.1.4.

$$R = \frac{rK_w}{K_r} \quad (2.1.4)$$

where:

R	=	radius of influence zone, L
r	=	radius of recharge well, L
K <sub>w</sub>	=	permeability of media surrounding well (i.e. gravel), LT <sup>-1</sup>
K <sub>r</sub>	=	permeability of refuse, LT <sup>-1</sup>

It was estimated that the ratio of  $K_w/K_r$  ranges from 30 to 50. Considering a well diameter of 60 cm (2 ft), the influence radius would range from 18 to 30 m (60 to 100 ft). It was then concluded that wells should be spaced no more than 60 m (200 ft) apart to ensure efficient wetting of the waste mass. A short-coming of Equation 2.1.4 is that it ignores the effect of flowrate on the radius of influence.

## 2.2 Leachate Collection System

The leachate collection system (LCS) is the ultimate barrier between the environment and landfill leachate and is thus subject to intense scrutiny during both the design and installation phases. One of the most common concerns associated with leachate recirculation systems is that they cause an increased threat to groundwater quality. The extra leachate loading on the LCS due to recirculation may result in increased leachate heads on the liner. It is therefore important to discuss some of the design equations and recent LCS research efforts. There are two basic liner types currently in use, the composite (Figure 2.2.1) and double-composite liner.

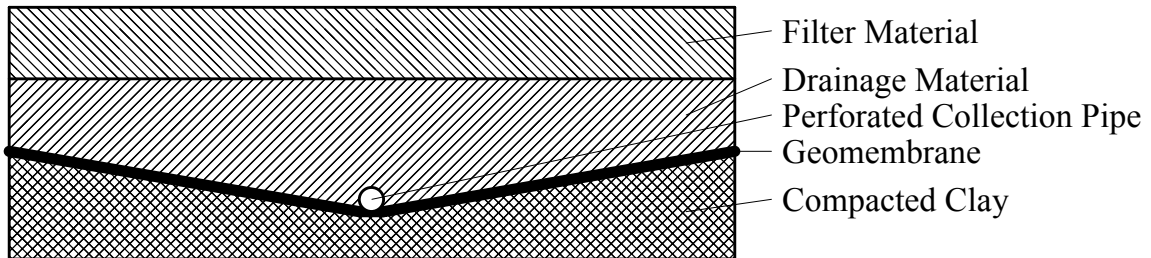


Figure 2.2.1. Schematic diagram of a composite liner system.

Because of federal regulations (US EPA, 1988a) which restrict leachate head to 30 cm, much attention has been devoted to predicting this value. It is controlled by the drainage length, drainage slope, permeability of the drainage materials, and the leachate arrival rate.

McBean et al. (1982) used Darcy's Law in conjunction with the law of continuity to develop an equation to predict the leachate head on the liner based on anticipated infiltration rates, drainage material permeability, distance from the drain pipe, and slope of the collection system. McBean's equation is very cumbersome and requires an iterative solution technique to determine the free surface profile.

Oweis and Biswas (1993) examined the effect of percolation rate on the leachate mound. The study consisted of the development of direct equations which were



compared to results obtained using the USGS MODFLOW software package. The equations developed can be used to predict changes in the leachate mound as a result of changes in the percolation rate. Results indicated that the leachate mound was very sensitive to changes in the percolation rate and that effective capping decreases the mounding of leachate within the fill.

Several EPA guidance documents have presented Equation 2.2.1 (US EPA, 1989) for use in predicting the maximum saturated depth over the liner.

$$y_{\max} = L \left( \frac{r}{K} \right)^{1/2} \left[ \frac{KS^2}{r} + 1 - \frac{KS}{r} \left( S^2 + \frac{r}{K} \right)^{1/2} \right] \quad (2.2.1)$$

where:

- $y_{\max}$  = maximum saturated depth over the liner, L
- $L$  = maximum distance of flow, L
- $r$  = rate of vertical inflow to the drainage layer,  $LT^{-1}$
- $K$  = hydraulic conductivity of the drainage layer,  $LT^{-1}$
- $S$  = slope of the liner, dimensionless

McEnroe (1993) used the extended Dupuit assumptions for unconfined flow to develop equations (2.2.2a, b, and c) for the steady state saturated depth over a liner.

$$Y_{\max} = (R - RS + R^2S^2)^{1/2} \left[ \frac{(1 - A - 2R)(1 + A - 2RS)}{(1 + A - 2R)(1 - A - 2RS)} \right]^{1/2A} \quad (2.2.2a)$$

for  $R < 1/4$

$$Y_{\max} = \frac{R(1 - 2RS)}{1 - 2R} \exp \left[ \frac{2R(S - 1)}{(1 - 2RS)(1 - 2R)} \right] \quad (2.2.2b)$$

for  $R = 1/4$

$$Y_{\max} = (R - RS + R^2S^2)^{1/2} \exp \left[ \frac{1}{B} \tan^{-1} \left( \frac{2RS - 1}{B} \right) - \frac{1}{B} \tan^{-1} \left( \frac{2R - 1}{B} \right) \right] \quad (2.2.2c)$$

for  $R > 1/4$

where:

$$\begin{aligned} R &= \frac{r}{K \sin^2 \alpha}, \text{ unitless} \\ A &= (1 - 4R)^{1/2}, \text{ unitless} \\ B &= (4R - 1)^{1/2}, \text{ unitless} \\ S &= \tan \alpha, \text{ slope of liner, unitless} \\ Y_{\max} &= \frac{y_{\max}}{L}, \text{ dimensionless maximum head on the liner,} \\ y_{\max} &= \text{maximum head on the liner, L} \\ L &= \text{horizontal drainage distance, L} \\ \alpha &= \text{inclination of liner from horizontal, degrees} \\ K &= \text{hydraulic conductivity of the drainage layer, } LT^{-1} \\ r &= \text{vertical inflow per unit horizontal area, } LT^{-1} \end{aligned}$$

McEnroe developed a dimensionless form of the equation recommended by the US EPA, Equation 2.2.1 above. This dimensionless equation has the form shown below in Equation 2.2.3. McEnroe compared Equation 2.2.3 to Equation 2.2.2 and found that for values of  $R$  less than one the EPA equation significantly over-predicted  $Y_{\max}$ .

$$Y_{\max} = R^{1/2} \left[ 1 - \frac{(1 + R)^{1/2} - 1}{R} \right] \quad (2.2.3)$$

Where all variables were previously defined.

The equations for the calculation of the maximum head on the liner, presented above, may be used by designers to calculate a maximum allowable pipe spacing based on the maximum allowable design head, anticipated leachate loading rate, slope of the liner, and permeability of the drainage materials.

Equation 2.2.4 has been recommended for use in determining the spacing between collection pipes in a LCS using a geonet between the liner and gravel (US EPA, 1989).

The use of a geonet rather than natural materials increases the pipe spacing distance considerably.

$$\theta_{\text{reqd}} = \frac{qL^2}{4h_{\max} + 2L\sin\alpha} \quad (2.2.4)$$

Where:

- $\theta_{\text{reqd}}$  = transmissivity of geonet,  $L^2T^{-1}$
- $L$  = distance between collection pipes,  $L$
- $h_{\max}$  = maximum head on liner,  $L$
- $q$  = infiltration from a 25 year 24 hour storm,  $LT^{-1}$

$\alpha$  = slope of drainage system, degrees

Leachate collection systems are commonly constructed with layered materials as shown in Figure 2.2.1. The intent of this design is to use fine-grained materials on top of coarser grained materials in order to filter out materials that may clog lower layers or the drain pipes. Yeh et al. (1994) investigated wicking effects within the drainage layers of the collection system. The wicking effect is a result of capillary forces and may enhance spreading while impeding vertical moisture flow. This effect is due to the difference in unsaturated flow characteristics at the interface between the two drainage media.

Capillary forces may make it more energy efficient for the leachate to spread horizontally in the fine-grained media rather than to enter the gravel layer of the collection system.

This effect is most noticeable for low flow, dry conditions with a fine-grained soil overlaying coarse media. Once a breakpoint saturation is reached in the fine-grained media, moisture will enter the coarse-grained material. The wicking effect may result in ponding above the fine-grained material. A suggested remedy was to use a three-media collection system consisting of fine-, medium-, and coarse-grained materials (top to bottom). This would decrease the interface difference in characteristics and thus decrease the wicking effect.

Koerner and Koerner (1995) discussed the possibility of clogging of the LCS particularly the filter media used whether it be a geotextile or a fine-grained media. A series of vertical flow studies were conducted using 100-mm rigid wall permeameters filled with various combinations of drainage materials underneath MSW. They found that when MSW was placed directly on top of the gravel in the drainage system, no filter

material was used, leachate would buildup in the waste layer but was removed quickly once it reached the gravel media. The permeability of systems which used a combination of gravel and a filter material declined much more rapidly than the permeability of the gravel only drainage systems. A small amount of fine particles was observed to migrate through the gravel-only system over time. They also discussed the possibility that carbonate present in the coarse media may react with the leachate and cause agglomeration of the media. The limestone used in this study had a carbonate content of five percent and did not exhibit any agglomeration. They concluded that a decrease in the permeability of the drainage media should be anticipated when designing the LCS.

Landfilling operations in the United States have generally focused on isolating the solid waste mass from the environment. Isolation has been accomplished through the use of natural and synthetic environmental barriers as well as complex systems for the capture and removal of both leachate and gas. The intent of this design approach was to limit and hopefully stop the biodegradation of the waste mass by limiting waste exposure to moisture. It has been shown repeatedly, that the environmental barriers used to isolate the landfill from the environment fail to one degree or another and the landfill becomes a contaminant source and often biological activity restarts. It has been suggested in the past decade that a more environmentally responsible operation method may be to expose the waste mass to moisture via leachate recirculation thereby enhancing biodegradation processes and simultaneously stabilizing the waste mass, treating the leachate moving through the fill., and increasing the life expectancy of the landfill through volume reduction.

Miller et al. (1991a) documented a landfill excavation project which examined a 10 year old PVC liner and collection system. They found that the geotextile filter around the collection pipe was clogged and prevented the leachate from flowing out of the fill. The collection pipe was crushed, but once the filter was removed leachate began to flow. The liner showed a significant loss of plasticizers which decreases the flexibility while increasing the tensile strength of the membrane. This loss was attributed to contact with leachate. Liner material in the anchor trench which had not been exposed to leachate was still flexible. The original seams, while still intact, were easily separated by hand. These results indicate that settlement of the media below or shifting of the media above the liner may compromise the liner and that the structural integrity of the collection pipe may be a concern.

### 2.3 Hydraulic Characteristics of Municipal Solid Waste

In order to understand and study leachate flow characteristics it is imperative to collect information on the hydraulic properties of solid waste. Obviously, these properties will have a direct effect on the results of any project studying leachate routing just as the hydrologic properties of the subsurface media will affect a groundwater modeling study.

### 2.3.1 Permeability

Oweis et al. (1990) determined saturated permeabilities for MSW based on a series of constant rate pumping tests on a 11-m (35-ft) leachate mound in a MSW landfill in northern New Jersey. The non-equilibrium equations of Theis and Boulton and the straight line solutions of Jacob were applied to the drawdown data collected. The study identified a range of saturated permeabilities for MSW of  $10^{-3}$  to  $10^{-5}$  cm/s. The study also led to the conclusion that the laws governing moisture movement in soils can be applied on a macroscale to MSW.

A more recent study by Bleiker et al. (1993) calculated a permeability range of  $10^{-4.2}$  to  $10^{-7}$  cm/s for solid waste samples from the Brock West Landfill, Toronto, Ontario. This study also demonstrated that as density increases, permeability decreases, suggesting that with increasing compaction, permeability decreases.

Townsend et al. (1994) applied Zaslavsky's wetting-front infiltration equation (Equation 2.3.1) to leachate ponds.

$$i = K_{v,s} \frac{H + L}{L} \quad (2.3.1)$$

where:

$i$	=	infiltration rate, $LT^{-1}$
$K_{v,s}$	=	the vertical, saturated hydraulic conductivity, $LT^{-1}$
$H$	=	depth of ponded water, L
$L$	=	vertical length of saturated wetting front, L

Using Equation 2.3.1, a permeability of  $10^{-6}$  cm/s was determined for the waste at the Alachua County Landfill. The values for infiltration,  $i$ , and the ponded water depth,  $H$ , were determined by measurement, while the value of wetting-front length,  $L$ , was estimated based on the volume of leachate infiltrated and an estimated available storage volume of 30% in the waste. The assumptions involved in the estimation of the vertical length of the saturated wetting front and the available moisture content lead to some question as to the accuracy of the prediction of the permeability.

### 2.3.2 Unsaturated Flow Properties

Straub and Lynch (1982) were the first researchers to report on the application of unsaturated flow theory to the solid waste landfill. Power law Equations (2.3.2 and 2.3.3) were used to model the unsaturated characteristics of MSW.

$$h = h_s \left[ \frac{\theta}{\theta_s} \right]^{-b} \quad (2.3.2)$$

where

- $h$  = the suction head, L;
- $h_s$  = saturation suction head, L;
- $\theta$  = volumetric moisture content, dimensionless;
- $\theta_s$  = saturation volumetric moisture content, dimensionless; and
- $b$  = suction head fitting parameter.



$$K = K_s \left( \frac{\theta}{\theta_s} \right)^B \quad (2.3.3)$$

where:

$K(\theta)$	=	hydraulic conductivity at $\theta$ , $LT^{-1}$ ;
$K_s$	=	saturated hydraulic conductivity, $LT^{-1}$ ;
$\theta$	=	volumetric moisture content, dimensionless;
$\theta_s$	=	saturation volumetric moisture content, dimensionless; and
$B$	=	permeability fitting parameter, unitless.

Straub and Lynch assumed that due to the dominance of paper and fibrous materials in waste that the moisture retention characteristics of fine-grained materials could be used as a preliminary description for the moisture retention characteristics of solid waste.

Values for  $h_s$  of 100 cm,  $b$  of seven, and  $B$  of eight or nine showed good agreement with experimental results. The saturated hydraulic conductivity was set equal to the daily average moisture application rate while the saturated moisture content was set equal to the field capacity. Setting  $\theta_s$  equal to the field capacity was justified by the assumption that leachate will not be produced until the moisture content exceeds the field capacity.

Field capacities ranging from 0.3 cm/cm to 0.4 cm/cm and as-placed moisture contents of 0.036 cm/cm to 0.205 cm/cm were reported. The as-placed moisture contents of 0.036 cm/cm and 0.205 cm/cm corresponded to waste with field capacities of 0.31 cm/cm and

0.375 cm/cm respectively. These wastes would require 27 and 17 cm of moisture per meter (3.2 and 2.0 in./ft.) of solid waste to reach field capacity, respectively

Korfiatis et al. (1984) used a 56-cm (22-in) diameter laboratory column packed with a heterogeneous mixture of approximately six-month old waste obtained from a MSW landfill to simulate the vertical movement of leachate within the landfill. The column was equipped with in situ pressure transducers to determine the relationship between suction pressure and saturation.

A 15-cm (6-in) diameter column packed with waste was used to determine the saturation/suction pressure curve. The column was packed with waste of known moisture content. After packing was completed, pressure measurements were taken. This procedure was repeated several times at different moisture contents in order to determine the characteristics of the saturation/suction pressure curve. The power law relationships proposed by Straub and Lynch (1982), Equation 2.3.2 and 2.3.3, were used to fit the data. The saturation suction head was determined to be 6.2 cm (2.45 in) of water. Measurements of the saturated moisture content ranged from 0.5 to 0.6; a value of 0.5 was recommended. The suction head fitting parameter,  $b$ , was determined to be 1.5. However, the measurement technique did not account for channeling and most likely underestimated the suction head fitting parameter,  $b$ . Channeling could be accounted for by increasing the suction head fitting parameter in models that use moisture diffusion theory to model unsaturated flow. The best correlation between the equations and experiments were obtained for  $b$  equal to four. The field capacity was found to vary from 20% to 30%. A value of 11 was recommended for the permeability fitting parameter,  $B$ .

Saturated hydraulic conductivities ranging from  $1.3 \times 10^{-2}$  cm/s to  $8 \times 10^{-3}$  cm/s were determined for waste samples subjected to the constant head permeability test.

A sensitivity analysis was performed analyzing the importance of  $b$  and  $B$ . It was found that doubling  $b$  had little effect but that increasing  $B$  from 10 to 11 increased the cumulative volume measurement by 30%.

A primary difference between the Korfiatis study and the Straub and Lynch study was the definition of  $\theta_s$  and  $K_s$ . Korfiatis defined  $\theta_s$  as the actual saturated moisture content whereas Straub and Lynch defined  $\theta_s$  as the field capacity of the refuse. Similarly, Korfiatis defined  $K_s$  as the measured saturated hydraulic conductivity while Straub and Lynch defined it as the moisture application rate.

An important conclusion drawn in the Korfiatis study was that the driving force of capillary diffusivity, the suction head, was negligible compared to gravitational forces once the saturation increased above field capacity. However, when the moisture content was below field capacity, capillary diffusivity was the dominant driving force. The results obtained were for a one-dimensional vertical flow situation. The study results also showed that the field capacity tended to increase after drainage had started. The authors hypothesized that this result indicated that secondary absorption and capillary action redistribute moisture into the waste from the primary flow channels. Results also indicated that the redistribution process was slow in comparison to the breakthrough time.

Noble and Arnold (1991) evaluated several engineering models for moisture transport within a landfill. Shredded newspaper waste used as a solid waste surrogate in

their laboratory experiments which were one-dimensional vertical flow situations. They developed the FULFILL program, a one-dimensional linearized finite difference solution of the Richard's equation (Equation 2.3.4), which includes the effects of gravitational forces.

$$\frac{\partial \theta}{\partial t} + \frac{\partial K(\theta)}{\partial z} - \frac{\partial}{\partial z} \left\{ D(\theta) \frac{\partial \theta}{\partial z} \right\} = 0 \quad (2.3.4)$$

where

$\theta$	=	volumetric moisture content, dimensionless
$K(\theta)$	=	hydraulic conductivity as a function of the moisture content, $LT^{-1}$
$D(\theta)$	=	moisture diffusivity, $L^2T^{-1}$
$z$	=	vertical coordinate, L
$t$	=	time, T

Noble and Arnold compared the power law equations (Equations 2.3.2 and 2.3.3) proposed by both Korfiatis et al. (1984) and Straub and Lynch (1982); to an exponential relationship (Equations 2.3.5 a, b, and c).

$$K = K_s e^{\gamma(\theta^*-1)} \quad (2.3.5a)$$

$$h = h_{\max} e^{-a\theta^*} \quad (2.3.5b)$$

$$\theta^* = (\theta - \theta_{ad}) / (\theta_s - \theta_{ad}) \quad (2.3.5c)$$

where:

$K$	=	hydraulic conductivity, $LT^{-1}$
$K_S$	=	saturated hydraulic conductivity, $LT^{-1}$
$h$	=	suction head, L
$h_{max}$	=	maximum suction head, L
$a$	=	fitting parameter, unitless
$\gamma$	=	fitting parameter, unitless
$\theta^*$	=	normalized moisture content, dimensionless
$\theta$	=	moisture content, dimensionless
$\theta_S$	=	saturated moisture content, dimensionless
$\theta_{ad}$	=	air, dry moisture content, dimensionless

Noble and Arnold reported the following values for use with Equations 2.3.5a, b, and c;  $h_{max}$  equals 22.5 cm (8.84 in) of water,  $a$  equals five or seven, and  $\gamma$  equals 11. An important distinction between the exponential and power equations is that the exponential equations predict a maximum value of  $h_s$  at dry conditions ( $\theta$  equals zero) whereas the power equations predict an infinite value.

Al-Yousfi (1992) performed a statistical analysis based on probabilistic entropy, the concept that a system has a natural tendency to approach and maintain its most probable state, and maximization and minimization techniques ("game theory") in combination with randomness and observation techniques ("information theory") to develop Equations 2.3.6 a and b for hydraulic conductivity as a function of saturation.

$$K(\theta) = -K_s(\theta - \theta_r) \ln \left\{ 1 + \left[ \exp\left(\frac{-1}{\theta - \theta_r}\right) - 1 \right] \frac{\theta}{\theta_s} \right\} \quad (2.3.6a)$$

for  $\theta > \theta_r$

$$K(\theta) = 0 \quad (2.3.6b)$$

for  $\theta < \theta_r$

where

$K(\theta)$	=	hydraulic conductivity as a function of the moisture content, $LT^{-1}$
$\theta$	=	volumetric moisture content, dimensionless
$K_s$	=	saturated hydraulic conductivity, $LT^{-1}$
$\theta_r$	=	residual moisture content, dimensionless
$\theta_s$	=	saturated moisture content, dimensionless

It was assumed that the hydraulic conductivity was zero for saturations less than the residual saturation. Equation 2.3.6 compares well with the equations from Noble and Arnold and Korfiatis et al. as can be seen in Figure 2.3.1. It is interesting to note that Al-Yousfi's equation was derived strictly from statistical theory and required no data.

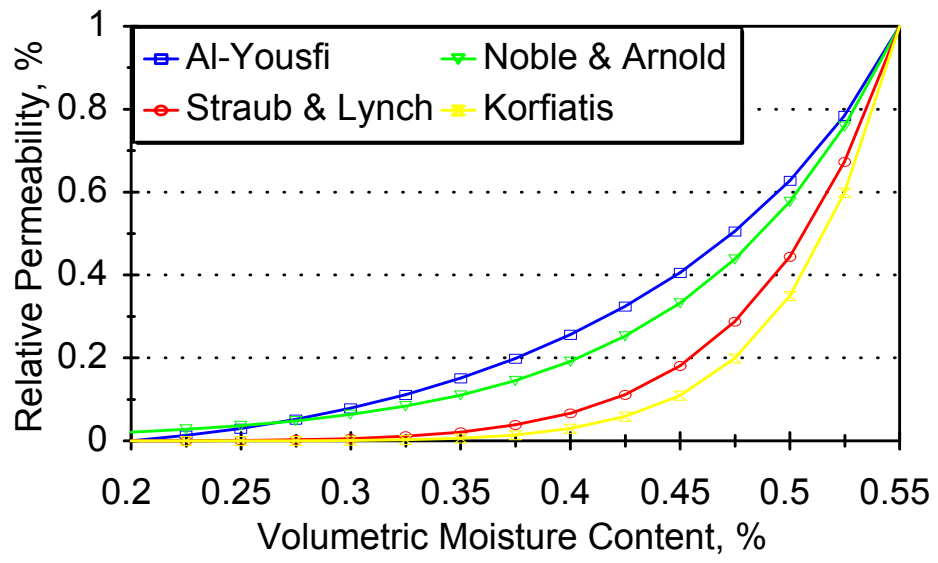


Figure 2.3.1. Comparison of unsaturated flow relationships for MSW.

### 2.3.3. Moisture Flow Patterns

Zeiss and Major (1992) used a column study to measure patterns of moisture flow in MSW and determine which variables were affected by flow channeling and waste compaction. Each column used consisted of two 55-gal drums welded together to give a total column height of 1.8 m and a diameter of 0.57 m. The columns were filled with hand-picked MSW with particle sizes ranging from 2.9 to 15.3 cm with a nine-sample average of 9.05 cm. Waste density, porosity, field capacity, apparent hydraulic conductivity, and flow channeling were analyzed as a function of compaction. Compaction was applied via 100 kg plates, the number of plates used varied the amount of compaction. Project results are summarized below in Tables 2.3.1 and 2.3.2.

Table 2.3.1. Summary of Material Property Data (Zeiss and Major, 1992).

Compaction	Compaction Factor, $\text{m}^3/\text{m}^3$	Density, $\text{kg}/\text{m}^3$	Porosity, $\text{m}^3/\text{m}^3$	Field Capacity, $\text{m}^3/\text{m}^3$
Low	1.6	165.6	0.582	0.123
Medium	1.67	186.7	0.532	0.141
High	2.85	304.5	0.474	0.143



Table 2.3.2. Summary of Hydraulic Property Data (Zeiss and Major, 1992).

Compaction	Average Flow Velocity, cm/s	Drainage Rate, L/min	$K_{us}^{\prime 1}$ Initial, cm/s	$K_{us}^{\prime 1}$ Final, cm/s
Low	0.0365	0.85	0.0214	1.12E-3
Medium	0.0324	1.03	0.0175	1.35E-3
High	0.0280	0.90	0.0134	1.18E-3

<sup>1</sup>apparent unsaturated hydraulic conductivity

These results led to a variety of conclusions and speculations by the authors. While it has been suggested that compaction will alter leachate routing, project results indicated that flow channels were not significantly affected by increases in density and decreases in porosity even with compaction ratios of up to 2.9. Compaction resulted in very little change in leachate arrival times, field capacity, and unsaturated hydraulic conductivities. The field capacity at 0.136 (volumetric) was significantly lower than the Hydraulic Evaluation of Landfill Performance model (HELP) default of 0.294. Flow characteristic measurements (hydraulic conductivities and breakthrough times) suggested that leachate velocities and leakage rates are four orders of magnitude higher and breakthrough times seen are five orders of magnitude lower than the HELP model default values. The field capacity and flow characteristic measurements indicate that leachate leakage from the waste layers will occur more quickly and at higher flow rates than predicted by the HELP model.

Zeiss and Ugucioni (1994) used the same columns as the Zeiss and Major study described above to evaluate mechanisms and patterns of leachate flow with special attention to macro-pore effects (channeling). The columns were filled with hand-picked MSW with particle sizes ranging from 8 to 22 cm. Moisture flow sensor plates and tensiometers were installed at three levels within the waste mass. The moisture flow sensor plates consisted of a wire grid strung with porous cups which contained two electrodes. When liquid entered a flow cup, a complete circuit was formed which registered on an external light panel. Each of the columns was subjected to different compaction. Overburden pressure was applied using 100 kg plates placed on top of the waste mass. Research results on flow channeling indicated flow through less than 45% of the available area for all samples tested. It was also shown that the flow centroid moved significantly between layers. This result suggests that flow channels are not vertically aligned but rather meander through the waste mass. While flow channeling is an important flow mechanism, the gradual decrease in capillary pressure measurements indicates that Darcian flow is also occurring. Field capacities, the moisture volume at which drainage begins, were found to be significantly lower at 0.07 and 0.15 than the default HELP model values of 0.23 to 0.36. The apparent hydraulic conductivity, the length of the column divided by breakthrough time, was determined to be  $6.14 \times 10^{-5}$  cm/s; the ultimate hydraulic conductivity, calculated from the steady state discharge rate, was determined to be  $6.08 \times 10^{-6}$  cm/s. The authors stated that project results indicate that while Darcian flow is experienced in the waste mass, it may not be the dominant flow mechanism. The development of a two domain, channeled and Darcian flow, is

suggested. However, the development of such a model requires that the nature of flow in channels and their representative length and diameter be determined.

Zeiss and Ugucioni (1997) attempted to confirm channeling, characterize flow regimes and determine the effects of infiltration rate and waste density on flow parameters. Additionally, the key flow parameters of practical field capacity, pore-size distribution index, effective storage, hydraulic conductivity, breakthrough times, and discharge rate were measured. Eight rectangular-steel containers (1.8 m X 1.6 m X 1.5m) filled with residential MSW and equipped with tensiometers and a grid of flow sensor cups (as described in the Zeiss and Ugucioni, 1994, study) were used in the study. Breakthrough times at 15 to 30 min (with two outliers of 25 and 40 hrs), occurred at times similar to previous studies while the apparent initial unsaturated hydraulic conductivity was slightly higher than previous studies. The authors felt that these results indicated that channeled discharge developed more quickly in this larger scale study than in the previous studies which used 55-gal drums to construct the column. A particularly interesting portion of the study attempted to characterize the flow regime in the channels through determination of the Reynolds number (Equation 2.3.7).

$$\text{Re} = \frac{\rho \cdot q \cdot d}{\mu} \quad (2.3.7)$$

where:

Re	=	Reynolds number
$\rho$	=	liquid density
q	=	specific discharge rate
d	=	average pore diameter
$\mu$	=	viscosity

The liquid density and viscosity are material properties and the specific discharge rate was determined experimentally. The average pore diameter was determined by injecting plaster into the waste and allowing it to harden. Horizontal cross sections were then cut across the waste and examined to determine the size of the plaster filled areas. The Reynolds number was determined to be greater than ten in five of eight cells inspected indicating that most cells were at the transition or exceeded Darcian (laminar) flow limits.

Moore et al. (1997) documented determination of hydraulic characteristics from full-scale leachate flow data generated by the Yolo County Bioreactor Landfill Project. The Yolo County Bioreactor Landfill Project consisted of two landfill cells, a control cell and an enhanced cell, with a 30.5 m x 30.5 m footprint and depth of 13.7 meters each. Both cells were equipped with moisture and temperature sensors. Liquid was added to the enhanced cell via 14 ‘trenches’ (3 m long, 1.5 m deep, 1m wide) placed on 6.67-m centers in the surface of the waste mass. Two of these trenches were only operated for

part of the study due to their proximity to gas collection wells. Leachate from these two trenches was short-circuiting and collecting in the gas wells. The cells were constructed simultaneously during the dry season and covered with impermeable membranes. Approximately 17% of the leachate recirculated channeled directly to the LCS, arriving within 24 hours of leachate application, for the first 34 days of operation. At day 35, leachate generation increased to 25% of the leachate input. This sudden increase in leachate generation was accompanied by a significant change in leachate chemistry and appearance. These changes in leachate generation and leachate chemistry indicated the breakthrough of Darcian flow. After day 55, leachate production increased until day 71 when it reached 47% of the leachate input. An ultimate unsaturated hydraulic conductivity of  $3.9 \times 10^{-4}$  cm/s was calculated using the landfill depth (38 ft) and a breakthrough time of 35 days. The waste mass achieved a final moisture content of 0.48 (dry basis), an increase of 48% from an estimated initial moisture content of 0.34. Mass balance results indicate that while leachate recirculation will result in immediate production of leachate, it will provide some attenuation in leachate production.

#### 2.4 Geotechnical Properties of Municipal Solid Waste

The geotechnical behavior of waste is of great interest to landfill designers and operators. Properties such as slope stability, settlement, and compaction characteristics of the landfill mass directly impact the design and operation of the landfill site. The

study of waste geotechnology is in its infancy and is complicated by the heterogeneous nature of waste.

Grisolia et al. (1991) conducted laboratory and field studies on MSW in an effort to define the geotechnical behavior (shear strength, compressibility, and permeability) of waste. The in situ studies consisted of static and dynamic penetration tests and plate-load tests. The penetration tests were strongly influenced by the heterogeneity of the waste matrix, hard bodies impacted the experiment considerably. The blow count and cone resistance varied considerably with depth. The plate load tests indicated a stress-strain modulus of 800 to 1600 kPa. The waste was shown to rebound approximately 45% of the realized settlement once the plate load was removed. The laboratory tests consisted of confined lateral and triaxial compression tests. The laboratory data indicated that waste undergoes a primary settlement phase characterized by large deformations. Later settlement is similar to the secondary settlement process exhibiting long term creep indicative of plastic adjustment of the soil fabric.

Wall and Zeiss (1995) approached landfill settlement from a geotechnical as well as biological perspective. It was estimated that a landfill may settle as much as 25 to 50% of its original thickness with biodecomposition mediated settlement accounting for 18 to 24% of the original thickness. Moisture addition was shown to enhance initial and primary settlement. However, studies indicated that neither oxygen addition nor bioenhancement effected the rate or amount of secondary compression. Biologically mediated settlement is the result of solids being converted to liquids. Skeletonization or

bridging in the waste mass may mask the effects of biological activity on secondary settlement.

Townsend et al. (1996) investigated the effect of leachate recirculation on landfill settlement as part of a study of the acceleration of landfill stabilization due to recirculation. The study was conducted at the Alachua County Landfill in Gainesville, FL. Ponds were used to recirculate leachate. Results indicated that the greatest degree of settlement 1.01 m, a 5.65% volume loss; occurred at the center of a closed leachate recirculation pond. The least settlement, 0.69 m, a 3.82% volume loss; occurred at the surveying point farthest from the leachate recirculation ponds. Due to the nature of the leachate recirculation pond, these large settlements did not compromise the pond structure. However, this degree of settlement could fracture the piping in a leachate recirculation trench or possibly tip a vertical leachate recirculation well.

## 2.5 Mathematical Models

Prior to undertaking any modeling effort, it is important to study similar modeling projects. This study aids in model selection, determination of data requirements, and prevents the duplication of research efforts.

A number of models have been developed to address the concerns associated with moisture movement within the landfill. These models fall into several categories:

- hydrologic water balances,
- saturated flow models,
- unsaturated flow models (one-dimensional and two-dimensional), and
- biochemical-hydrodynamic models.

The Hydrologic Evaluation of Landfill Performance Model (HELP) developed by Schroeder et al. (1984) is one of the most commonly used models for the evaluation of the leachate collection system (LCS) performance. It is presently in its third release. The HELP model simulates leachate movement via a quasi-two dimensional system. The landfill, including cap, waste, daily cover material, and LCS components, is modeled as a series of layers each with its own hydraulic properties. Precipitation events are modeled through a number of techniques including actual meteorological data sets and statistically derived artificial storms. This system enables the landfill professional to quickly assess the effect of various landfill designs and weather patterns. Leachate recirculation is specified as a percentage of the leachate collected to be recirculated and is uniformly applied to the landfill area. The HELP model uses the field capacity concept to model moisture storage. A layer, whether soil or waste, will not produce leachate until it has reached field capacity. Once field capacity is reached, any moisture added will result in the downward moisture movement.

Peyton and Schroeder (1988) verified the HELP model by simulating the performance of 17 landfills. The researchers found that the HELP model was useful for evaluating general landfill performance and generated reasonable water balance results.



However, the model was not well adapted to modeling single, specific field results. The researchers attributed this to the variability in specific site conditions even for identically constructed cells. The selection of cover material was also found to be critical as the permeability of the cover material directly influenced the calculation of the cumulative lateral drainage of stormwater.

Stephens and Coons (1994) used the HELP model to assess the performance of landfills in semiarid areas. They found that the HELP model results correlated well with field information. In particular, they found that the long-term infiltration rate calculated by the HELP model agreed well with the natural recharge rate calculated through a chloride mass balance. Results indicated that due to the low infiltration rates in arid and semi-arid areas, clay liners do not appreciably reduce long-term, post-closure seepage. It was noted that a clay liner would impede seepage if weather patterns were to change or extreme precipitation events occurred. The values for evaporative depth and field capacity were difficult to estimate but had a profound effect on model results. The evaporative depth was difficult to estimate due to the layering of soils in the cap and the unknown effect of refuse beneath the final cover. The estimation of field capacity was obscured by the fact that it has various definitions depending on the particular discipline addressing the topic. Additionally, the field capacity has been shown to increase with time in the landfill environment (Korfiatis et al., 1984). In order to produce conservative leachate production values, a low value should be chosen for both the evaporative depth and field capacity. Using large values for either of these two parameters may result in underprediction of leachate production and head on the liner.

Field and Nangunoori (1993) raised questions as to the accuracy and usefulness of the HELP model. Their research involved calibrating the HELP model using existing data from an active hazardous waste landfill and then attempting to predict the landfills behavior for the next 18 months. Results indicated that while the HELP model was useful for predicting long-term landfill behavior, it was highly inaccurate at predicting daily leachate production. They found specifically that the HELP model results were highly dependent on the input of precipitation event duration and intensity and that the time averaging techniques inherent to the model while applicable for long time periods were not appropriate when modeling short-term leachate production.

Hannoura et al. (1994) introduced modifications to the HELP code to adjust for nonlinear flow effects encountered at low Reynolds Numbers. Their work was based on saturated Darcian flow and does not directly address entrained air or unsaturated flow dynamics. The thrust of their changes was to introduce a non-linear term for the estimation of hydraulic conductivity. Their changes showed an increase in the prediction accuracy for uncovered landfills but a decrease in accuracy for covered landfills. Their conclusions indicated that leachate movement is subject to non-linear effects and that while the individual components of the HELP model perform well, their performance as a combined system is suspect. It was suggested that an integrated multi-phase model would be best to model leachate movement within the landfill.

Hatfield and Miller (1994) developed two models for the simulation of water balances at operating landfills. The Deterministic Multiple Linear Reservoir Model (DMLRM) simulates the landfill moisture balance as the combined surface and

subsurface discharges from three parallel reservoirs. Reservoirs one, two, and three were respectively, the upper 1.2 meters of the landfill, the interior of the landfill, and surface runoff discharges. Validation studies showed the model to have a 5.59% error in prediction of cumulative discharge and a average absolute error of 55.56% in prediction of incremental discharge volumes.

The Stochastic Multiple Linear Reservoir Model (SMLRM) was based on the same theory as the DMLRM with the exception that the three most sensitive parameters, precipitation interception efficiency for reservoirs one and three and the maximum feasible moisture content for the waste and cover soil, were defined as probability density functions. In addition to increasing the prediction accuracy to 3.95% and 48.04% for the cumulative and incremental discharge predictions respectively, the use of statistical functions enables SMLRM to be applied to other landfills where less data are available.

Baetz and Byer (1989) developed a model to aid operators in controlling the amount of leachate collected through modifications in the operation procedures. In particular, they found that increasing cover thickness offers declining percolation reduction and that vertical construction techniques significantly decreases leachate as compared to horizontal construction.

The Flow Investigation for Landfill Leachate model (FILL), Ahmed et al. (1992) and Khanbilvardi et al. (1995), uses a combination of saturated and unsaturated flow theory to model leachate movement. Unsaturated flow theory was used to simulate moisture flow through the waste mass while saturated flow theory was used to analyze the mounding of leachate in the collection system. The model results include moisture

contents at grid points within the waste mass and the depth of the leachate head on the liner. The model does not address leachate recirculation systems nor does it provide boundary conditions suitable for modeling leachate recirculation. While this is a two-dimensional model most of the flow appears to be constrained to the vertical direction due to the boundary conditions imposed.

Straub and Lynch (1982) made the first attempt to combine unsaturated flow and transport theory with landfill stabilization theory to simulate leachate flow and quality. The one-dimensional, vertical flow model was based on the supposition that the contaminated moisture present in the placed waste is first supplemented by infiltrating moisture which raises the moisture content to field capacity while leaching and solubilizing components from the solid waste mass. Once field capacity is exceeded, leaching begins. Thus, the first flow of leachate is highly contaminated. As liquid continues to infiltrate, the waste mass remains at field capacity and the leachate contaminants are diluted. The dilution process continues until equilibrium is reached between the leaching and dilution processes. The flushing effect implied by these assumptions minimizes the effect of moisture diffusion as compared to gravity drainage resulting in a strong moisture gradient and the propagation of a wetting front. It was assumed that the unsaturated properties associated with fine-grained materials could be used due to the dominance of paper and fibrous material in the waste mass. Results indicated that the landfill can be modeled as an unsaturated porous media and that ultimately, these concepts could be applied to field-scale problems.

Korfiatis et al. (1984) formulated and calibrated a mathematical model for the simulation of one-dimensional, vertical movement of moisture through waste. The mathematical model was based on the one-dimensional Richard's Equation for unsaturated flow using the power equations previously mentioned (Equations 2.3.2 and 2.3.3) for the interrelationship of saturation, suction head, and permeability. A laboratory scale leaching column was constructed using a 56-cm (22-in.) diameter by 1.8-m (72-in.) deep drum to simulate vertical moisture movement. Two experiments were run both used approximately six-month old waste obtained from a local landfill. Leachate was applied in a uniform manner to the upper surface using perforated tubing. In the first experiment, the waste moisture content was at or below field capacity. Leachate was first produced 222 hrs after the onset of moisture application. Results also indicated that the field capacity appeared to increase with time or that the amount of leachate stored increased after onset of drainage. In the second experiment the waste was at or above field capacity. Leachate was first produced 30 hrs after the onset of moisture application. Both experiments showed moisture re-distribution to be a slow process after the cessation of application. The results from the second experiment showed that 16.4 l of the 85.2 l applied were still retained 800 hrs after the cessation of application. Calibration of the model based on the experimental results indicated that setting the suction head fitting parameter equal to four and the permeability fitting parameter equal to 11 yielded the best results. A sensitivity analysis indicated that large change in the suction head fitting parameter,  $b$ , had little effect on the results, while small changes in the permeability fitting parameter,  $B$ , effected results significantly. These results suggests that hydraulic

conductivity dominates the diffusion process. It was concluded that capillary diffusivity contributes little at moisture contents above field capacity due to the large pore structure of the waste material which inhibits the development of large suction heads.

Demetracopoulos et al. (1986) performed a sensitivity analysis on the model formulated by Korfiatis et al. (1984). The analysis consisted of assessing model outputs for both unsaturated and saturated surface conditions. Unsaturated surface condition simulations were most sensitive to changes in hydraulic conductivity and the permeability fitting parameter,  $B$ . Grid and time-step size had little effect on simulation results. A grid size of 30 cm (1 ft) and time-steps of one day were recommended for simulating full-scale landfills. Saturated surface condition simulations were most effected by the time span over which rainfall events were averaged. Once again, grid and time step size had little effect on simulation results.

Noble and Arnold, 1991 used the FULFILL model, a one-dimensional model based on the Richard's Equation (Equation 2.3.4) for unsaturated flow, in conjunction with paper-filled columns to evaluate several models for moisture transport within the landfill. FULFILL calculates transient moisture content and flux profiles over time from specified top and bottom boundary conditions.

Vertical infiltration and capillary rise experiments were conducted to assess the predictive capabilities of FULFILL. The results from FULFILL were found to compare well with the experimental results.

Lee et al. (1992) developed LEAGA-1, a one-dimensional model based on a combination of unsaturated flow theory and biological decomposition theory, to predict

the quality of leachate emanating from the fill. Unsaturated flow was modeled using soil moisture diffusivity theory (Equation 2.5.1)

$$-\frac{\partial}{\partial z} \left\{ D(\theta) \frac{\partial \theta}{\partial z} \right\} + \frac{\partial}{\partial z} K(\theta) = \frac{\partial \theta}{\partial t} \quad (2.5.1)$$

where:

$z$	=	vertical displacement, L
$\theta$	=	moisture content, dimensionless,
$D(\theta)$	=	moisture diffusivity, $L^2T^{-1}$ ,
$K(\theta)$	=	permeability, $LT^{-1}$ , and
$t$	=	time, T

while biological decomposition was based on a three-phase sequential process of hydrolysis, acid formation, and methane formation. Model results agreed well with data gathered from a pilot-scale lysimeter. It was concluded that the use of unsaturated flow theory increased prediction accuracy and that the hydrolysis rate constant had the most profound effect on the leachate quality results. A hydrolysis rate constant of  $0.0008 \text{ day}^{-1}$  provided the best agreement between experimental and modeled data sets.