MOISTURE DISTRIBUTION EFFICIENCY AND PERFORMANCE EVALUATIONS OF BIOREACTOR LANDFILL OPERATIONS

by

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ABSTACT

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Bioreactor landfills are operated in a modern engineered way to accelerate waste decomposition, gas production, and waste stabilization. The major aspect of a bioreactor landfill operation is associated with the addition of supplemental liquid or leachate recirculation, and the effective operation primarily depends on efficient moisture distribution throughout the waste mass, which enhances performance. The performance of an effective landfill operation can be assessed by several indicators, i.e., leachate generation, gas production, and landfill settlement. Bioreactor landfill operations have several significant economic and environmental advantages, but the impact of efficient moisture distribution and the assessment of performance through combined indicators is not well established. Hence, explaining and quantifying such impact on performance monitoring is essential to understanding an effective operation.

The overall objective of this research was to monitor moisture distribution, due to leachate recirculation, throughout the landfill and to evaluate the performance of landfill operations. Leachate recirculation was performed through horizontal recirculation pipes and vertical injection wells. The City of Denton Landfill, in Denton, Texas, USA was selected as the site for the field investigations. A field program was conducted, using the electrical resistivity imaging (ERI) technique to determine moisture variations with time (one day, one week, two weeks) due to leachate recirculation through the horizontal and vertical recirculation systems. The data of field performance indicators, i.e., leachate generation, gas production, and landfill settlement, was collected from the landfill authority and analyzed to observe the bioreactor performance. Field leachate generation was compared with the Visual HELP model results to correlate it with the gas generation. The combined effect of indicators was analyzed to evaluate landfill performance. The research provides data on the significant factors of successful bioreactor landfill operations: the application frequency of leachate, and moisture distribution efficiency due to leachate recirculation through vertical injection wells. The research develops an understanding the effect of indicators and the assessment of landfill performance through evaluating the essence of individuals and combined indicators.

Scheduling the leachate recirculation is one of the most vital actions required for distributing the moisture in the underlying waste. A comprehensive understanding of moisture variations in a bioreactor landfill, by reason of circulating leachate, is important for determining the frequency of leachate recirculation. The estimated moisture content for the baseline study was 31.5% before the next cycle of leachate recirculation to the adjacent recirculation pipe. However, the moisture content after 1 day, 7 days and 14 days after leachate recirculation was found 49.52%, 40.48%, and 31.74%, respectively.

Several recirculation systems are currently being used at different locations across the world; however, vertical injection wells are the specific objects of interest in leachate recirculation due to their potential advantages over other available systems. Based on the results of the studies pertaining to vertical wells, the initial moisture content ranged from 31.5% to 36.5% before liquid was added through the vertical wells. The moisture content observed rose from 49.5% to 64.6% within one day after the leachate injection; however, it decreased one week after leachate injection, ranging from 40.12% to 47.03%. Two weeks after leachate injection, the moisture content ranged from 31.75% to 38.6%.

The performance of bioreactor landfills can be monitored by several indicators, i.e., moisture distribution, leachate generation, gas production, water balance, and landfill settlement. Combining the different parameters to assess the performance of a bioreactor landfill has not been widely investigated. The results from the water balance simulation model, Visual HELP, show that the actual leachate generation in the field is approximately 55% lower than the HELP model results. The reason that the leachate return from the landfill is lower might be that the added water/leachate is being partially used for gas production. Hence, an increase in gas generation was observed, increasing from 543.6 m^3/h (320 scfm) in 2010-2011 to 1087.3 m^3/h (640 scfm) in 2014-2015. Moreover, in some locations of the landfill cells, from 2014 to 2015, an approximate total of 1.45 m (4.8 ft.) of maximum settlement was found in the landfill.

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CHAPTER 1

INTRODUCTION

Background

Engineered landfilling is considered the most common, economical, and environmentally acceptable method of all solid waste disposal systems. The total amount of solid waste generated in United States in 2013 was 254 million tons, with 167 million tons (65.7% of the total generated waste) discarded into the landfills (USEPA, 2015). In conventional landfills the, decomposition rate of waste is slow because of minimal moisture retained in the waste. As a result, it takes a long time for total decomposition of landfilled waste to occur. The most common method used to speed up this process is the addition of moisture or recirculated leachate, as proposed by Pohland in the 1970s (Pohland, 1975). Landfills employing this process are known as bioreactor landfills or enhanced leachate recirculation landfills (ELR).

Bioreactor landfills are an alternative to conventional landfills and introduce the concept of adding supplemental water to the landfilled waste to increase microbial activities and enhance waste decomposition. The addition of moisture to the landfill allows better interactions among soluble substrates, soluble nutrients, and microorganisms to augment microbial activities (Barlaz et al., 1990). The leachate recirculation also has significant impacts on leachate composition, gas production, the leachate stabilization rate, and waste volume reduction, as investigated by Reinhert & Yousfi in 1996. The multiple studies of bioreactor landfills further describe the advantages of long-term risk reduction (Barlaz et al., 1990; Reinhart and Townsend, 1997; Pohland and Kim, 1999).

Enhanced microbiological activities help transform and stabilize the biodegradable fractions of MSW at a faster rate (Sharma and Reddy, 2004). The moisture distribution increases microbial growth, which also increases the rate of decomposition, thus the rate of settlement (Edil et al., 1990; El-Fadel et al., 1999; Hossain et al., 2003). This increase in the rate of settlement is beneficial because of the addition of air space before closure and the minimization of potential settlement-induced damage for the final cover (Benson, 2000). The rate of gas production is also increased, due to the enhanced waste decomposition, thereby improving the viability of gas-to-energy options (Klink and Ham, 1982; Findikakis et al., 1988; Barlaz et al., 1990; Mehta et al., 2002). Leachate treatment costs may also be reduced in bioreactor landfills (Pohland, 1975, 1980; Reinhart et al., 2002).

Several factors contribute to the overall effectiveness of a landfill. According to a study conducted by Bureau et al., (2005) the bioreactor performance depends on the design of the leachate collection system, variable quality of the injected leachate, and the short monitoring time. Water balance, slope stability, liner and final cover integrity, landfill gas production and emission, and landfill settlement have been observed to have an impact on the effectiveness of the bioreactor landfills (EPA Report, September, Louisville, Kentucky, 2006; Morris and Barlaz, 2011; Bareither et. al., 2010; EPA Report, Cincinnati, Ohio, August, 2005). Additionally, leachate recirculation promotes landfill stabilization by maintaining optimum moisture contents and causing a more effective transfer of microbes and nutrients throughout the waste mass.

Problem Statement

A bioreactor landfill's successful operation primarily depends on the addition of supplemental liquid or leachate recirculation. The distribution and extent of added moisture or leachate with time offers more efficient operation by accelerating waste decomposition, thereby optimizing the landfill's performance and resulting in economic benefits and environmental sustainability.

Landfills are frequently considered for urban development, but have limitations due to problems associated with the differential settlement, leachate generation, and gas emissions. Among all the practical problems, settlement may be the most crucial one. Most of the global MSW is dumped into non-regulated landfills, and the generated methane is emitted to the atmosphere. Part of the methane generated in landfills can be captured and used as a renewable energy source. Modern landfills try to collect the biogases produced by anaerobic digestion. Decomposition of organics provides the source of gas production in landfills, and decomposition products are the primary constituents of landfill gas. The nature of MSW and the stage of decomposition determine the landfill gas composition at any given time. The potential of landfill gas production depends on the components of the MSW.

Economically and environmentally, there are significant benefits to dealing with bioreactor/ELR landfills. To maximize the benefits, however, it is important to understand the indicators that play a major role in its overall efficiency. Moisture distribution, water balance, settlement, gas production, waste decomposition, and stabilization of landfills are the major indicators for operating a bioreactor landfill efficiently. Few studies have been conducted on the individual indicators, making it difficult, if not impossible, to observe their individual influence on the bioreactor landfill. Very limited studies have been conducted on the frequency of leachate recirculation and the combination of performance indicators to evaluate the efficiency of bioreactor landfills.

Research Objectives

The overall objective of this research work is to monitor moisture distribution due to leachate recirculation in landfills and to evaluate the performance of a bioreactor landfill operation. A continuous field monitoring program was performed, using Electrical Resistivity Imaging (ERI) to observe moisture variations within the landfill. The Visual HELP program was utilized to estimate leachate generation as a part of the water balance in landfills. The frequency of leachate recirculation, water balance, leachate generation, gas production, and settlement play important roles in evaluating the performance of a bioreactor landfill operation. The specific objectives of this current research work are to:

a) Establish a field monitoring program to determine moisture distribution, using resistivity imaging;

b) To monitor moisture distribution due to leachate recirculation through horizontal recirculation pipes;

c) To monitor moisture distribution due to leachate recirculation through vertical injection wells;

d) To study the effect of water balance on bioreactor landfill operations;

e) To study the effect of settlement and the addition of space gain on a bioreactor landfill operation;

f) To study the effect of gas production and energy generation on a bioreactor landfill operation;

g) To study the effect of combined indicators to evaluate the performance of a bioreactor landfill operation.

Dissertation Organization

Chapter 1 begins with an introduction, followed by a problem statement and objectives of the research. An extensive literature review is presented in Chapter 2. The rest of the report is divided into three papers. The first paper discusses the leachate recirculation frequency required to operate a bioreactor landfill successfully. In this paper, moisture distribution with time has been measured, due to leachate recirculation through a horizontal pipe. The second paper focuses on moisture distribution due to leachate recirculation through vertical injection wells. The performance of the vertical well is evaluated in this paper. Finally, the third paper discusses the performance and efficiency of a bioreactor landfill operation. Moisture distribution, leachate recirculation, leachate generation, gas production, and landfill settlement are monitored and evaluated with time. These papers are followed by a summary and conclusions.

CHAPTER 2

LITERATURE REVIEW

Municipal Solid Waste Landfill

According to the US Environmental Protection Agency (EPA), a discrete area of land or excavation which receives household waste is called a municipal solid waste (MSW) landfill. A MSW landfill also receives other types of non-hazardous wastes, including commercial solid waste, non-hazardous sludge, conditionally-exempt generator waste, and industrial non-hazardous solid waste. These types of landfills are regulated according to the principal of subtitle D of the Resource Conservation and Recovery Act (40 CFR Part 258 in Federal regulations 1991).

Municipal Solid Waste Characteristics

The characteristics of MSW are critical to the analysis and design of conventional and bioreactor landfills to meet long-term performance requirements. The variations in these characteristics are sensitive to the safety and cost of landfills. Unfortunately, the behavior of MSW is heterogeneous, due to containing hard inclusions. However, the evaluation and prediction of MSW landfill behavior depend on reliable knowledge of MSW characteristics. Determination of the characteristics of MSW usually requires physical sampling, by drilling into the waste mass, and time-consuming laboratory testing. According to Fassett et al., (1994), determining the characteristics and conditions of MSW is challenging because: 1) landfill materials are inconsistent and heterogeneous in nature; 2) it is difficult to obtain samples of sufficient representative size in field conditions; 3) there is a lack of generally accepted sampling and testing procedures; and 4) the MSW properties change with time, depth, and location. A discussion of the MSW characteristics includes physical composition, moisture content, unit weight, and organic content.

Physical Composition

Municipal solid waste (MSW) generally consists of everyday constituents that are consumed and discarded. There are different categories of wastes, including paper products, glass, metal, plastics, rubber and leather, textiles, wood, food wastes, yard trimmings, and miscellaneous inorganic wastes. The variation of the composition depends on each type of waste and also on time. The individual components of physical composition make up a solid waste stream, commonly given as a percentage by weight. Information on the physical composition of MSW is necessary to the selection and operation of equipment at a landfill, assessment of the feasibility of resource and energy recovery, and the analysis and design of landfill disposal facilities (Tchobanoglous et al., 1993). Municipal solid waste is heterogeneous in nature, which reflects the economic status and lifestyle of a community. According to the EPA, 254 million tons of trash were generated, and 87 million of those tons were recycled and composted in 2013. Figure 2.1 represents the total MSW generation over a long period of time and shows that the rate has increased with time.

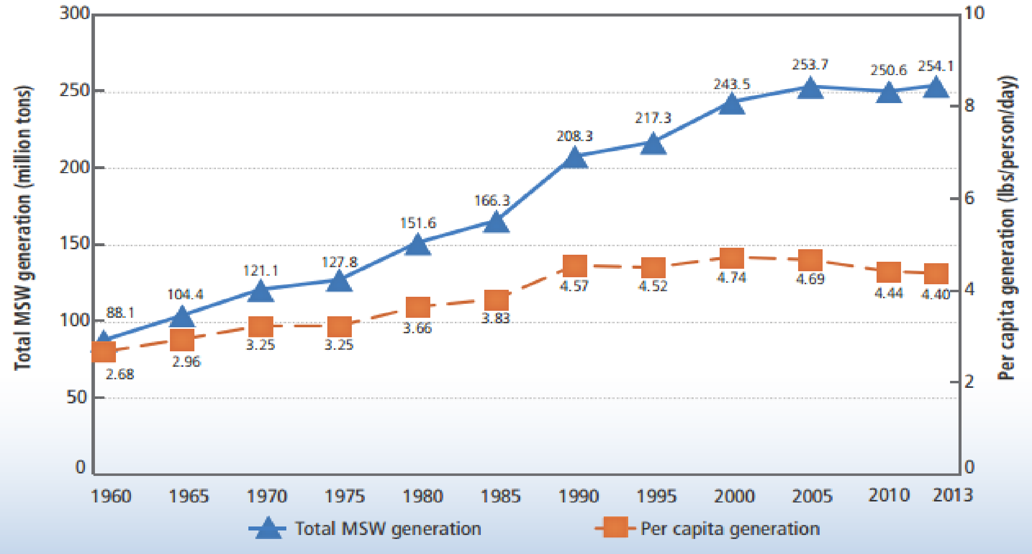


Figure 2.1 MSW generation rates from 1960 to 2013

The generation of MSW in 2013 in the United States was comprised of paper & paperboard, accounting for 27%; yard trimmings and food wastes, accounting for another 13.5%; plastics, accounting for12.8%; metals, accounting for 9.1%; rubber, leather & textiles, making up 9%; wood, at around 6.2%; glass, at around 4.5%, and other miscellaneous wastes of 3.3%, as presented in Figure 2.2.

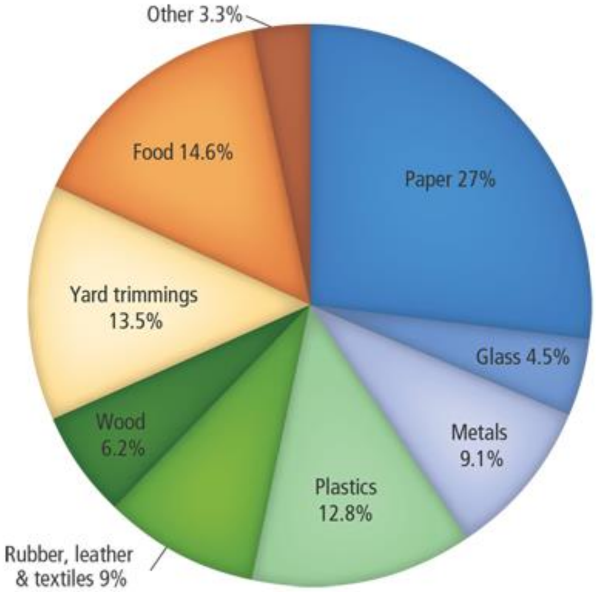


Figure 2.2 Total MSW generation by material type (EPA, 2013)

Moisture Content

The measurement of the moisture content of MSW depends on the amount of liquid within the waste. Fassett et al., (1994) reported that the moisture content of MSW landfills is highly dependent on several interrelated factors: composition of the waste (e.g., organic content), type of waste (e.g., liquid waste or sludge), waste properties (e.g., hydraulic conductivity and field capacity), local climactic conditions (e.g., precipitation and season), landfill operating procedure (e.g., leachate circulation), effectiveness of leachate collection and removal system (e.g., leachate head control), and amount of moisture generated by biological processes within the landfill.

According to Reddy (2006), moisture content can be defined in three different ways: a) the ratio of the liquid mass to the dry mass of the waste, b) the ratio of the liquid mass to the wet mass of the waste, and c) the ratio of the volume of liquid to the volume of the waste. The most commonly-used method in the solid waste field is the wet weight method. Pohland (1975) stated that moisture content is the factor that most influences the acceleration of waste decomposition. The increased moisture content enhances microbial growth by allowing better contact between insoluble substrates, soluble nutrients, and microorganisms (Barlaz et al., 1990).

Yochim et al., (2013) stated that the moisture content of landfills depends on various parameters, such as precipitation, type of capping, waste type, site management, and the geological and hydrogeological conditions of the site. Moisture content in the conventional landfill varies from 15 to 40% (Tchobanoglous et al., 1993); however, optimum moisture content in a bioreactor landfill operation is more than 65% w/w (Tchobanoglous et al., 1993; Rodriguez et al., 2004; and Imhoff et al., 2007).

Townsend et al., (1996) observed that moisture content increases after leachate recirculation. The reported moisture content of a MSW landfill in North Central Florida was 31.3% and 457% before and after leachate recirculation, respectively.

Sowers (1968) and CalRecovery, Inc. (1993) reported that the gravimetric moisture content on a dry basis of MSW usually ranged between 21% and 35%. According to Zornberg et al., (1999), the average dry gravimetric moisture content was 28% in a MSW landfill located in Southern California. The dry gravimetric moisture content of fresh MSW collected from the Orchard Hills landfill in Illinois was 44% (Reddy et al., 2009).

Unit Weight

The unit weight of municipal solid waste is defined as the weight of waste per unit volume. It indicates the compactness of the waste in a certain volume. The unit weight of solid waste varies, depending on it composition; state of decomposition; degree of control during placement, such as thickness or absence of daily cover; amount of compaction; total depth of landfill; the depth from which the sample is taken, etc. (Oweis & Khera, 1990). According to Fassett et al., (1994), meaningful estimation of the unit weight of solid waste depends on i) the composition of municipal solid waste, including daily cover and moisture content; ii) the method and degree of compaction; iii) the depth at which the unit weight is measured; and iv) the age of the waste.

Several studies have reported a wide range of unit weight values of MSW. Landva and Clark (1990) conducted a study in a landfill in Canada, where the unit weight ranged from 6.8 to 16.2 KN/m^3 for MSW. Unit weights ranging from 3 to 9 KN/m^3 for fresh waste with poor compaction, 5 to 7.8 KN/m^3 for moderate compaction, and 8.8 to 10.5 KN/m^3 for good compaction were reported by Fassett et al., (1994). Kavazanijan et al., (1996) determined the unit weights of Southern California landfills based on a correlation with shear wave velocity measurements. The reported unit weights ranged from 10 to 13 KN/m^3 near the ground surface to 13 to 16 KN/m^3 at a depth of 30m. In a bioreactor landfill, the unit weight of MSW may exceed the reported value due to the higher moisture contents Kavazanijan (2001).

A direct field measurement and spectral surface wave analysis (SASW) surveys were performed by Zornberg et al., (1999) to measure the unit weight for the waste at a

MSW landfill situated in Southern California. The obtained unit weight ranged from 10 to 15 KN/m^3 at a depth of between 8m to 50m below the landfill surface. Hossain et al., (2003) estimated the unit weight of degraded samples, as shown in Table 2.1. They reported that unit weight increases with the increment of degradation phase, as higher degradation contains more fine particles.

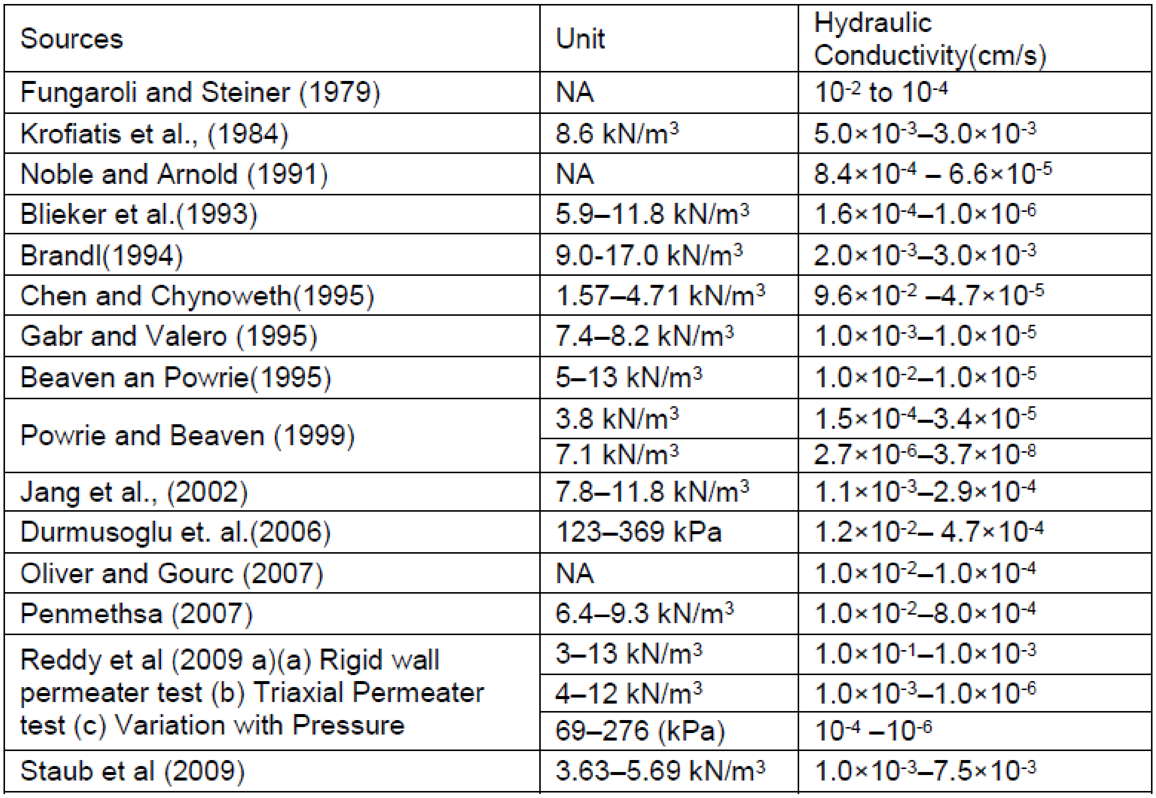
Table 2.1 Unit weight in different degradation phases (Hossain et al., 2008)

Phase	Unit Weight (kN/m3)
I	8.5-9.1
II	9.2-9.8
III	10.1-10.3
IV	10.7-11.2

Hydraulic Conductivity

The hydraulic conductivity (HC) of MSW depends on several parameters, including compaction effort, particle size, porosity, composition, degree of saturation, and depth within the landfill. The influence of particle size, material type, and degree of saturation on HC was evaluated by Hossain et al., (2008) in a laboratory scale study. According to Reddy (2009), HC decreases for degraded MSW, as it contains more fine materials. Waste hydraulic conductivity is important for the designer, as moisture distribution mainly depends on HC. The nature of HC in very crucial, as MSW is a heterogeneous material. HC also affects the effective distribution of stresses and, therefore, shear strength (Dixon and Jones, 2005). Several laboratory studies were performed to measure the HC of MSW, and the values are shown in Table 2.2.

Table 2.2 Hydraulic conductivity of MSW based on laboratory studies



Sources	Unit	Hydraulic Conductivity(cm/s)
Fungaroli and Steiner (1979)	NA	10^{-2} to 10^{-4}
Krofiatis et al., (1984)	8.6 kN/m^3	5.0×10^{-3}–3.0×10^{-3}
Noble and Arnold (1991)	NA	8.4×10^{-4} – 6.6×10^{-5}
Blieker et al.(1993)	5.9–11.8 kN/m^3	1.6×10^{-4}–1.0×10^{-6}
Brandl(1994)	9.0-17.0 kN/m^3	2.0×10^{-3}–3.0×10^{-3}
Chen and Chynoweth(1995)	1.57–4.71 kN/m^3	9.6×10^{-2} –4.7×10^{-5}
Gabr and Valero (1995)	7.4–8.2 kN/m^3	1.0×10^{-3}–1.0×10^{-5}
Beaven an Powrie(1995)	5–13 kN/m^3	1.0×10^{-2}–1.0×10^{-5}
Powrie and Beaven (1999)	3.8 kN/m^3	1.5×10^{-4}–3.4×10^{-5}
	7.1 kN/m^3	2.7×10^{-6}–3.7×10^{-8}
Jang et al., (2002)	7.8–11.8 kN/m^3	1.1×10^{-3}–2.9×10^{-4}
Durmusoglu et. al.(2006)	123–369 kPa	1.2×10^{-2}– 4.7×10^{-4}
Oliver and Gourc (2007)	NA	1.0×10^{-2}–1.0×10^{-4}
Penmethsa (2007)	6.4–9.3 kN/m^3	1.0×10^{-2}–8.0×10^{-4}
Reddy et al (2009 a)(a) Rigid wall permeater test (b) Triaxial Permeater test (c) Variation with Pressure	3–13 kN/m^3	1.0×10^{-1}–1.0×10^{-3}
	4–12 kN/m^3	1.0×10^{-3}–1.0×10^{-6}
	69–276 (kPa)	10^{-4} –10^{-6}
Staub et al (2009)	3.63–5.69 kN/m^3	1.0×10^{-3}–7.5×10^{-3}

Types of MSW Landfill

A MSW landfill is primarily utilized for permanent storage and containment or “dry cell.” The basic idea is to reduce environmental impacts by minimizing the amount of water entering the waste, thereby restricting the formation of leachate and gas. However, experience indicates that the system may become ineffective with the ages of containment and may have a long-term risk of uncontrolled leachate and gas leaks. In recent years, the concept of dry permanent storage has shifted toward “wet cell,” which has several advantages (Maurer, 1994; Krol et al., 1994). Generally, the two types of MSW landfill are conventional landfill (dry cell) and bioreactor landfill (wet cell).

Conventional Landfill

A conventional landfill is a traditional landfill that is primarily used as a place to dispose of refuse and other waste materials by dumping them and covering them with soil. It is a system of trash and garbage disposal, which essentially means that it is a method of filling in or extending usable land. In earlier times, a conventional landfill was mainly used as a disposal site to reduce contamination of the surrounding environment. Sometimes conventional landfills are called sanitary landfills, where non-hazardous waste is buried in between earth layers and is finally compacted to a certain level.

Bioreactor Landfill

A bioreactor landfill is an alternative approach to a conventional landfill, in which leachate recirculation is conducted and is vital to the operational purpose. According to Cheremisinoff and Morresi (1976), the bioreactor is not a new idea, as leachate has been used for a long time, not only to temporarily avoid leachate treatment, but also to enhance waste degradation and generate gas. A massive anaerobic bioreactor landfill, operated under controlled conditions, is a relatively new invention. Two main operating conditions were discussed in the first EPA Workshop (1981): a) the moisture content must be held at field capacity, and b) the pH must be controlled near neutral.

The bioreactor technology involves the addition of leachates, liquids, or sewage sludge; controlled temperatures; and supplemental nutrients which provide control and optimized operation. A bioreactor landfill operation may also involve the addition of air.

Based on operation and waste biodegradation mechanisms, three different kinds of bioreactor landfills, anaerobic bioreactors; aerobic bioreactors; and aerobic-anaerobic (hybrid) bioreactors; have been constructed and operated worldwide (Warith et al., 2005). A generalized schematic bioreactor landfill diagram is illustrated in Figure 2.3.

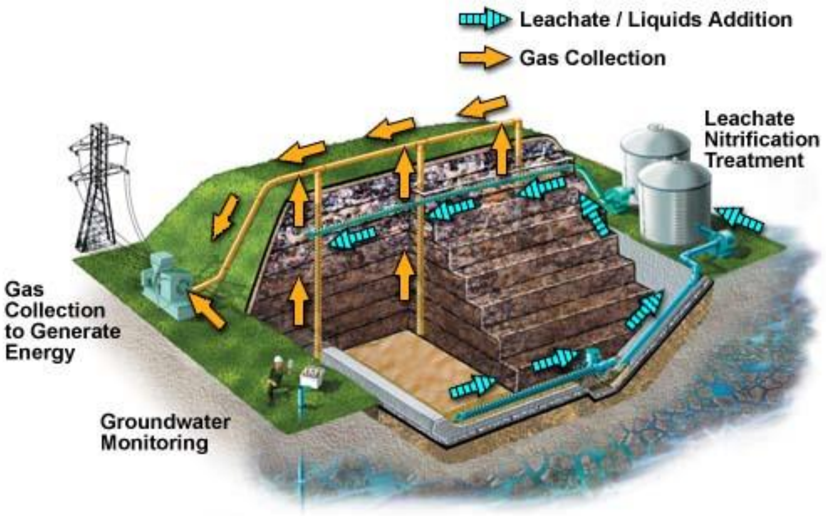


Figure 2.3 Schematic of bioreactor landfill (courtesy waste management)

Advantages of a Bioreactor Landfill

A bioreactor landfill has several advantages over the conventional landfill, as stated by the US EPA:

(a) Decomposition and biological stabilization occur in years rather than in decades in “dry tombs;”

(b) Lower waste toxicity and mobility due to both aerobic and anaerobic conditions;

(c) Reduced leachate disposal costs;

(d) A 15 to 30 percent gain in landfill space due to an increase in density of waste mass;

(e) Significantly increased LFG generation that, when captured, can be used for energy use on-site or sold; and

(f) Reduced post-closure care.

Karthikeyan & Joseph (2006) described the advantages of engineered bioreactor landfills, as follows:

(a) The generation and recovery of LFG under controlled conditions are enhanced, which in turn improves the economics for energy production.

(b) Bioreactor landfill operations reduce environmental impacts on groundwater, surface water, and the neighboring environment by containing the leachate and controlling the LFG emissions. It also controls the greenhouse gas emissions to the environment.

(c) Landfill space is increased by accelerating microbial degradation of solid waste and removal of inert end products through periodical landfill mining. The bioreactor landfill cells can be reused as a new landfill due to mining, and the end product can be used as compost material. The opportunity to reuse the bioreactor landfill cells and end products highly improves the economics of the bioreactor cell technology.

(d) The biological and chemical transformation of both organic and inorganic constituents are enhanced within the landfill air space. Bioreactor operation reuses generated leachate for recirculation, which reduces leachate treatment and operating costs.

(e) The operation of a bioreactor landfill minimizes long-term environmental risk and liability through rapid degradation, smaller amounts of leachate migrate into the subsurface, and LFG recovery. Proper operation of a bioreactor landfill will reduce post-closure monitoring costs.

(f) Overall contamination of a landfill is reduced due to controlled operation.

Operational Practices of Bioreactor Landfill

The main approach to ELR landfill operation and practice to date has been to contain and isolate the contents. Two major operations are, i.e., 1) leachate recirculation and 2) gas collection. One of the main reasons for leachate recirculation is to protect the environment from contamination. An engineering design and constructed envelope is utilized to encapsulate and drain the waste and to prevent, or at least minimize, the escape of landfill leachate into the environment. According to Lee and Jones (1993), if the constructed envelope requires no active intervention or management of the waste, the system is called “dry tombs.” On the other hand, an actively-managed envelope requires the design and implementation of containment measures, waste treatment, and a management program, and is known as a “wet cell.”

An active intervention and management approach requires several considerations. Various types of biological and biochemical processes occur within the landfill envelope, which eventually, with time, change the properties of the contained waste and produce leachate and gas. Leachate recirculation is not a new idea. Owners and operators of landfills have long used this liquids strategy, either to temporarily avoid leachate treatment or to enhance waste degradation and generate gas (Cheremisinoff and Morresi, 1976).

According to the EPA Workshop convened in 1981, there are two main operating conditions that must be maintained:

(i) the moisture content must be held at field capacity, and

(ii) the pH must be controlled near to neutrality.

There are some specific measures that can be taken to accelerate the decomposition process of organic materials and effectively shorten the time of the “reactor” period of a landfill (Baccini, 1988). These are:

(i) shredding or “homogenizing” the waste,

(ii) controlling moisture additions,

(iii) controlling sewage sludge additions, and

(iv) using aerobically or partially decomposed waste to reduce the acid phase.

Liquid management strategies are primarily subsets of natural attenuation, removal/treatment/discharge, or leachate recycling. Natural attenuation required geomembrane liners when the first regulations were promulgated. The attenuation was generally regarded to be adequate, even with low-permeability clay soil liners. A study was conducted by Dwyer (1995), in which he observed that natural attenuation has made somewhat of a resurgence for arid and semiarid landfill sites. The current liquids management strategy is to contain the waste within the liner and use extremely low permeability cover systems. As a result, liner system durability and functioning are key issues for long lifetimes and adequate performance of the associated materials.

There are some other important issues that have significant influence on the operation and practice of an ELR landfill. They are as follows:

(i) Liner system integrity

(ii) Filter and/or operations layer

(iii) Daily cover material

(iv) Final cover issues

(v) Waste stability concerns

The most major consideration for the operation and practice of an ELR landfill is the collection of gas. Municipal solid waste landfills can generate tremendous quantities of gas at the time of waste degradation. As a result, a gas collection and removal system for an ELR landfill needs to be installed early and designed for large flow. According to the 2000 EPA Workshop, a gas collection and removal system can be designed and operated to:

(i) Maximize landfill gas collection and control

(ii) Minimize occasional landfill fires or ensure that appropriate actions are taken should a fire occur.

Leachate Recirculation Systems

A bioreactor landfill operation mainly depends on the adding supplemental liquid into the landfill. The addition of liquid through a leachate recirculation system (LRS) enhances waste decomposition (Pohland, 1975; Barlaz et al., 1990; Pacey et al., 1999; Reinhart et al., 2002; Mehta et al., 2002; Warith, 2002; Benson et al., 2007; Bareither et al., 2008a). Leachate recirculation through LRS has several advantages which include: i) reducing the risk of final cover damage by settling the waste mass, ii) increasing the capacity of the landfill, iii) reducing leachate treatment cost, iv) enhancing gas production, and v) minimizing post-closure monitoring time and cost (Barlaz et al., 1990; Reinhart and Townsend, 1998; Pohland and Kim, 1999; Doran, 1999; and Mehta et al., 2002).

LRS generally consists of horizontal trenches, vertical wells, infiltration blankets, and direct surface applications (Reinhart and Townsend, 1997). The direct surface applications have been changed to subsurface methods over time. Haydar and Khire (2005) divided leachate recirculation techniques into two categories: surface application and subsurface application.

According to Qian et al., (2002) and Townsend et al., (2008), leachate recirculation can be conducted by two methods, as presented in Table 2.3. Of these methods, horizontal trenches and vertical wells are the most common techniques used to recirculate leachate into the solid waste mass.

Table 2.3 Categories of LRS in Landfill

Mode	Types
Surface systems	Spray irrigation, drip irrigation, tanker truck application, infiltration ponds, leach fields and surface trench
Subsurface systems	Horizontal trench, vertical injection well, buried infiltration galleries, permeable blanket

Horizontal Recirculation System

Bareither et al., (2010) studied bioreactor landfills in North America and reported that the distribution of leachate is limited when the surface pits and vertical wells are employed, and that improved distribution is obtained using horizontal trenches. Several researchers reported typical-size spacing and components of the horizontal trench system (Miller and Emge, 1997; Townsend and Miller, 1998; Reinhart and Carson, 1993; Reinhart et al. 2002; Benson et al., 2007). The typical horizontal trenches are 0.6 to 1.0m wide and 0.6 to 1.0m deep; spacing ranges from 4 to 9m vertically and 18 to 61m horizontally.

In horizontal recirculation trench construction, perforated pipe is utilized at the center of the trench, and relatively high conductivity drainage materials, e.g., gravel, coarse sand, crushed glass, and shredded tires are used as backfilled materials (Haydar and Khire, 2005). The perforated pipe delivers liquid to the permeable filter material, and the liquid is distributed to the surrounding waste. SWANA (2002) stated that typical injecting pressures of leachate recirculation and horizontal spacing range from 0 to 5m and 3 to 30m, respectively. Townsend and Miller (1998) conducted a field study on horizontal trenches where shredded tires were used as backfilled materials.

Miller and Emge (1997) conducted a study on enhancing the performance of a leachate recirculation system to enhance design and operation. They stated that the horizontal distribution system is a network of perforated pipes installed in various lifts of waste. Uniform leachate distribution throughout the landfill is achieved by the system. A schematic cross section of a horizontal recirculation system is shown in Figure 2.4.

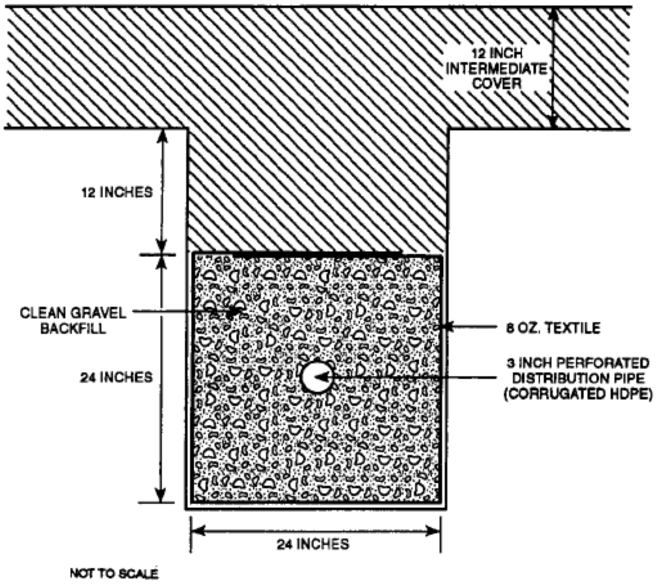


Figure 2.4 Cross section of horizontal recirculation system (Miller and Emge, 1997)

A case study was performed by Reinhart (1996) on full-scale experiences with leachate-recirculating landfills. Horizontal trenches were dug into the waste and filled with permeable materials, such as automobile fluff, gravel, or tire chips. Perforated pipe was utilized for leachate recirculation, and the cross section is presented in Figure 2.5.

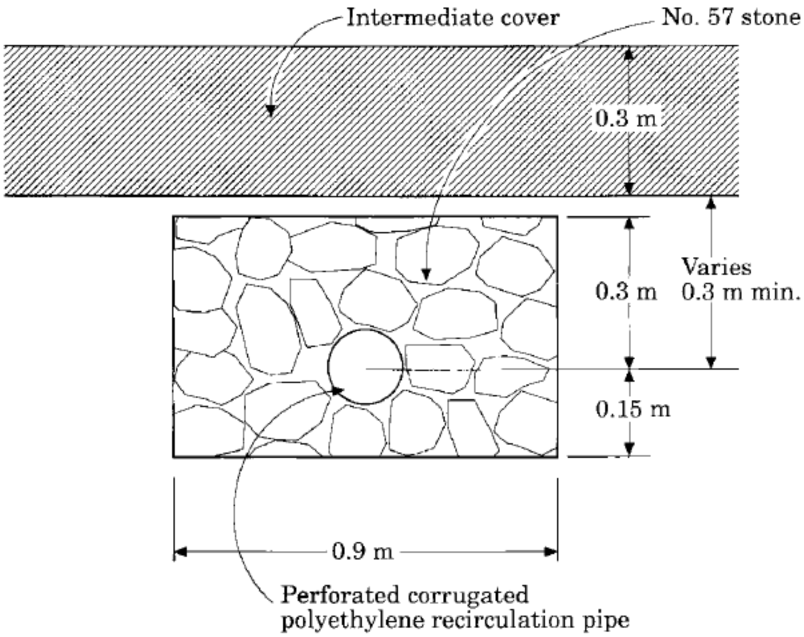


Figure 2.5 Horizontal leachate recirculation system (Reinhart, 1996)

Most landfill operators prefer horizontal recirculation systems during the active landfilling phases, as it is cost effective and less time consuming (Townsend, 2008). The installation procedure of horizontal recirculation systems combines three steps: trenching, pipe installation, and backfilling, as shown in Figure 2.6.

Figure 2.6 Construction of the horizontal trench (Townsend, T., 2008)

Vertical Recirculation System

Vertical injection wells are relatively common in retrofit landfills, where the installation of horizontal trenches are either not cost effective or not possible. These methods offer minimum exposure pathways and good all-weather performance with a relatively large amount of leachate recirculation (Townsend et al., 1995; Reinhart and Al-Yousfi, 1996; Miller and Emge, 1997; Warith et al., 2001; Mehta et al., 2002; Jain et al., 2005; Haydar and Khire, 2005; Benson et al., 2007; Khire and Mukherjee, 2007). The performance of vertical injection wells has been evaluated in several US landfills as a part of the leachate recirculation system (Reinhart et al., 1995; Jain et al., 2005; Benson et al., 2007).

Jain et al., (2005) conducted a study on the performance evaluation of vertical wells in the New River Regional Landfill (NRRL) located in Union County, Florida. They observed that the depth of leachate injection is one of the important factors dictating the amount of leachate to be added. In their study, a vertical well cluster model was utilized, which included 11 perforated vertical pipes, with high permeable backfill material. Surface seeps, gas collection system efficiency, and differential settlement were also observed throughout the study. The dimensions of the vertical wells were as follows: diameter of approximately 5.0 cm, depth, ranging from 6.1 to 18.3m, and the screen heights ranging from 3.0 to 6.1m. The schematic diagram of a vertical well cluster system is presented in Figure 2.7.

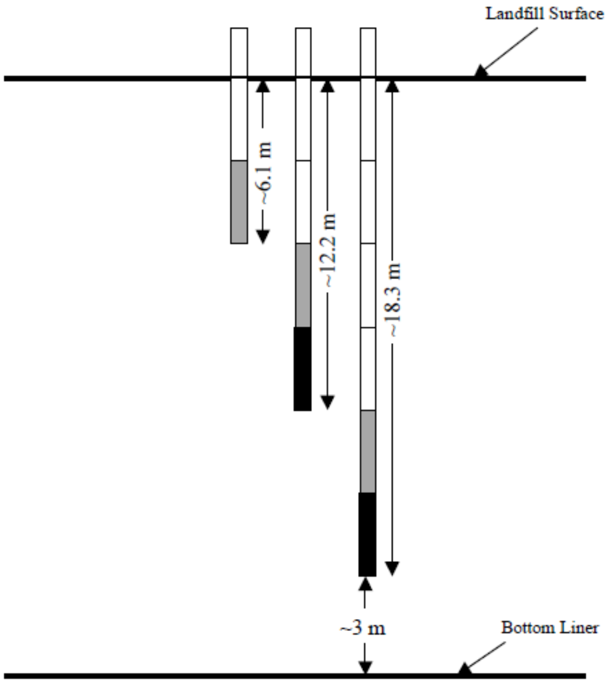


Figure 2.7 Schematic of a vertical well cluster (Jain et al., 2005)

Several researchers conducted studies on the performance of vertical injection wells, describing numerous advantages. Reddy et al., (2012) observed that the VW system offers uniform and adequate liquid distribution without causing problems such as excessive pore pressure and excessive differential settlements. Figure 2.8 shows the conceptual simulated model that was used by the investigators. Khire and Mukherjee (2007) numerically evaluated key design variables of vertical leachate recirculation system, using HYDRUS 2D. Jain et al., (2010) performed a numerical study using SEEP/W to present design input values. Table 2.4 represents the typical dimensions of a vertical well that were used in different studies.

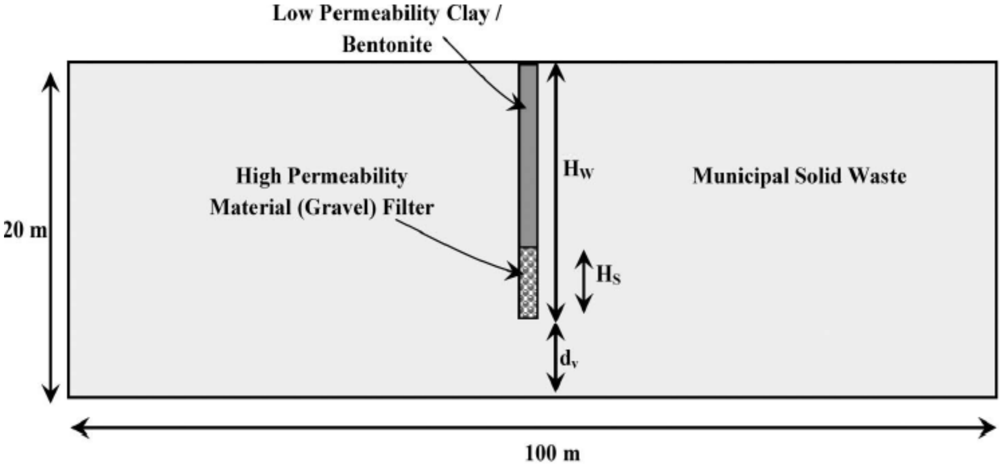


Figure 2.8 Conceptual model for vertical well (Reddy et al., 2012)

Table 2.4 Typical vertical well dimensions

Study	Well Diameter (m)	Well Depth (m)	Screen Length (m)
Jain et al., 2005	0.05	6.1-18.3	3.0-6.1
Khire and Mukherjee, 2007	0.05-0.1	17	3
Jain et al., 2010	0.025-2.5	5	2.5
Reddy et al., 2012	0.3	11.5	3

Moisture Distribution in Bioreactor Landfill

The degradation process of MSW is very slow due to inadequate moisture and inappropriate distribution of microbes and nutrients within the solid waste mass in the conventional landfill (Sharma and Reddy, 2004; Reddy, 2006; Kulkarni and Reddy, 2012). The slow degradation of MSW causes various problems, which are associated with environmental concerns, including: a) settlement continues for a long time, b) landfill gas production is minimized, and c) post-closure monitoring periods are increased. A bioreactor landfill is a modern concept that minimizes all the issues related to conventional landfills by allowing additional moisture through leachate recirculation or supplemental added water, and using different types of leachate recirculation systems. Various laboratory studies were conducted to observe moisture distribution in landfills.

A field study was performed by Bendz et al., (1997) to evaluate the infiltration of water through cover soil and the leachate generation in a landfill within a short period of time after its construction. Moisture content of soil cover and MSW samples were estimated using neutron probes and drilling samples, respectively. The observed results indicate that leachate generation occurs due to the infiltration of high moisture through soil. Figure 2.9 represents the annual moisture variations with time in the landfill cells.

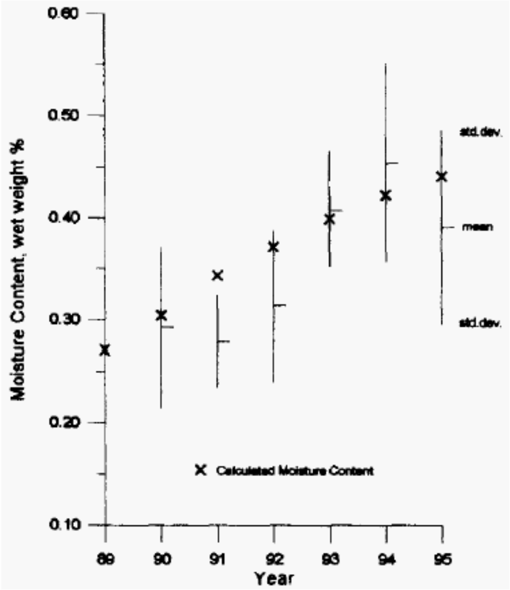


Figure 2.9 Total moisture content measured in the municipal solid waste sample (Bendz et al., 1997)

Gawande et al., (2003) estimated the in situ moisture content of municipal solid waste, using electrical resistance sensors, in Orange County landfill, Florida. Electrical resistance sensors measured the resistance between two electrodes, and the water content was determined by using correlation. The observed results indicated that the fraction of saturation increased with a decrease of sensor resistance, as presented in Figure 2.10.

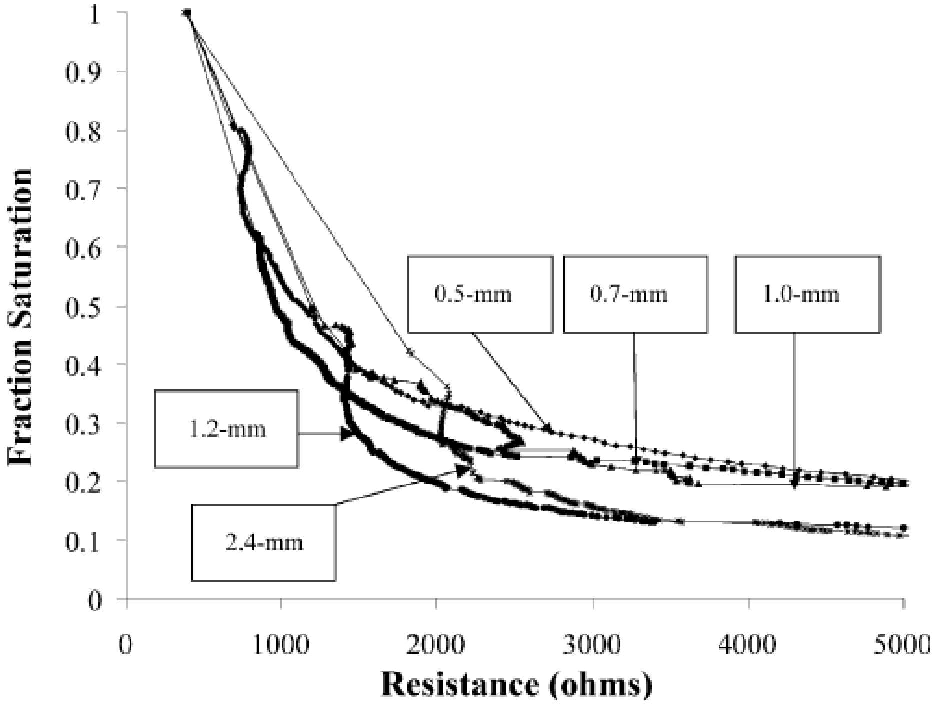


Figure 2.10 Fraction saturation with sensor resistance (Gawande et al., 2003)

Guerin et al., (2004) conducted a field study to monitor moisture distribution due to leachate recirculation in a landfill in France. Electromagnetic slingram mapping and electrical sounding or electrical 2D imaging were utilized to measure moisture variations. They investigated moisture levels during and after leachate recirculation through an injection borehole and a vertical borehole, using electrical 2D imaging. The results presented in Figure 2.11 indicate that the moisture content increases initially with time, but decreases after a certain period of time.

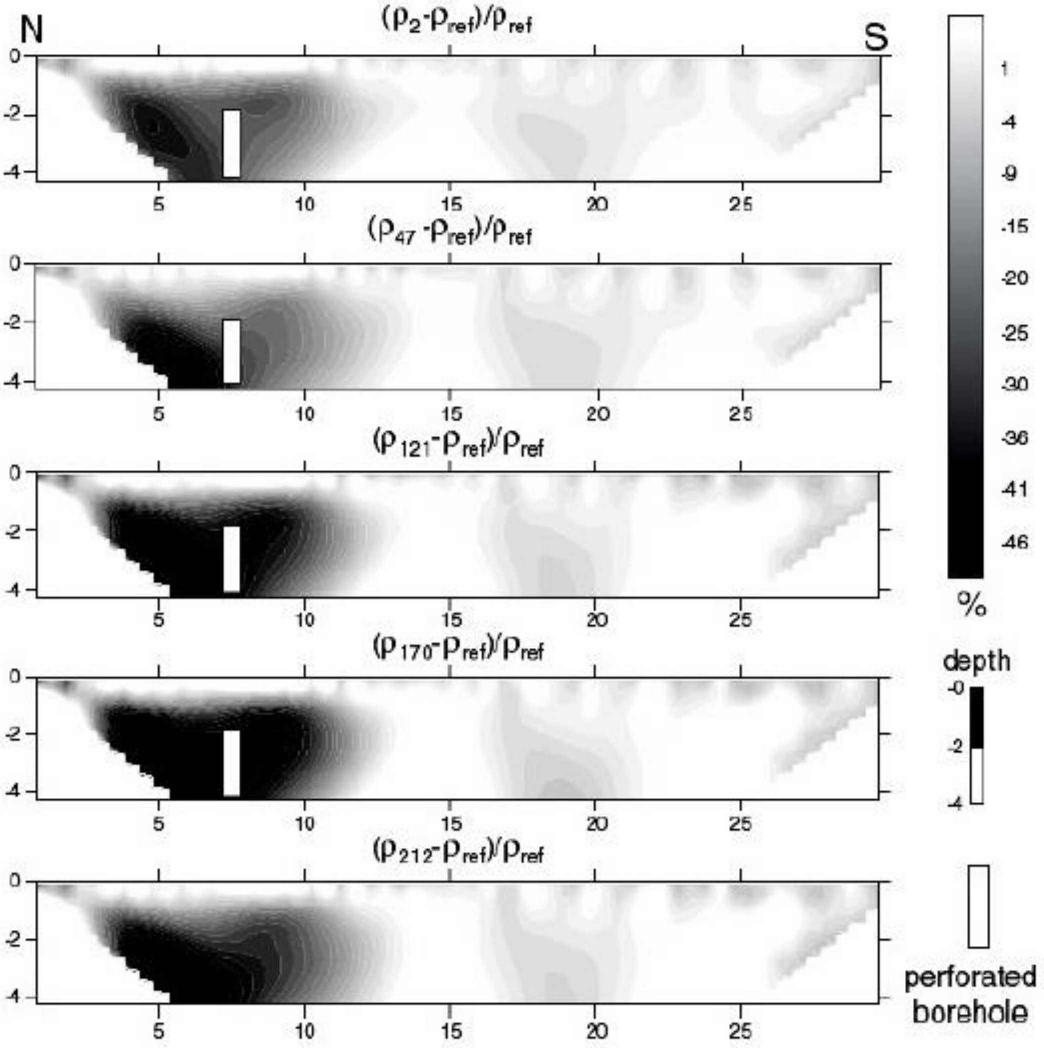


Figure 2.11 Resistivity variations (%) during and after injection in the bioreactor landfill (Guerin et al., 2004)

Grellier et al., (2006) utilized electrical resistivity tomography to conduct a field investigation in the Orchard Hills landfills in Davis Junction, Illinois, US. The objective of the study was to monitor moisture variations due to leachate recirculation through installed recirculation lines. The observed results, presented in Figure 2.12, show that the resistivity value decreases with time during recirculation. The decreased resistivity values indicate the increment of moisture.

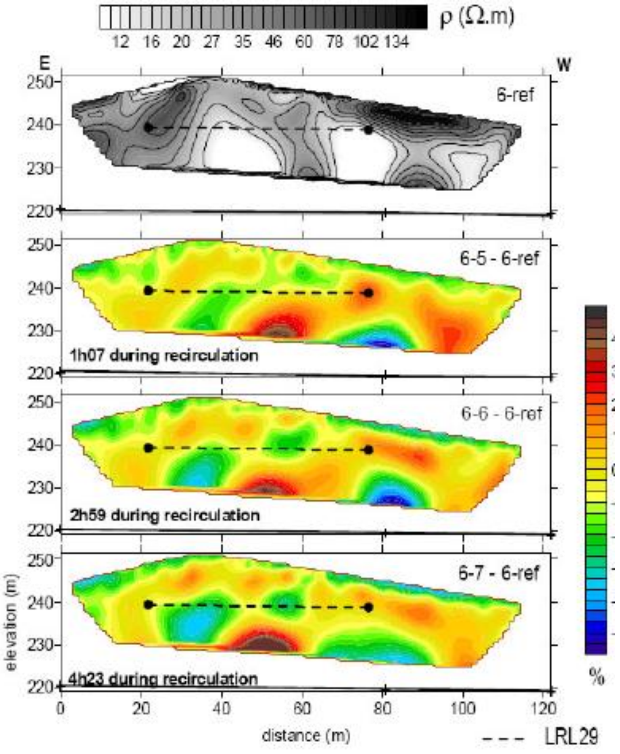


Figure 2.12 Resistivity variations during leachate recirculation (Grellier et al., 2006)

In situ moisture variations, including neutron probe, electrical resistance sensors, electromagnetic techniques, electrical resistivity tomography, partitioning gas tracers, and fiber optic sensors, were studied as review of the state of the art methods for measuring water in landfills (Imhoff et al., 2007). The results of partitioning gas tracers and fiber optic sensors were presented, as were the results of other techniques previously mentioned and conducted by other researchers. The partitioning gas tracer test has injection and extraction tracers, where extraction tracers move due to the affinity for the water phase. Field tests were conducted by Han et al., (2006) in the Sandtown Landfill operated by the Delaware

Solid Waste Authority (USA). Figure 2.13 depicts the gas tracer elution curves, indicating that the normalized concentration decreases with time.

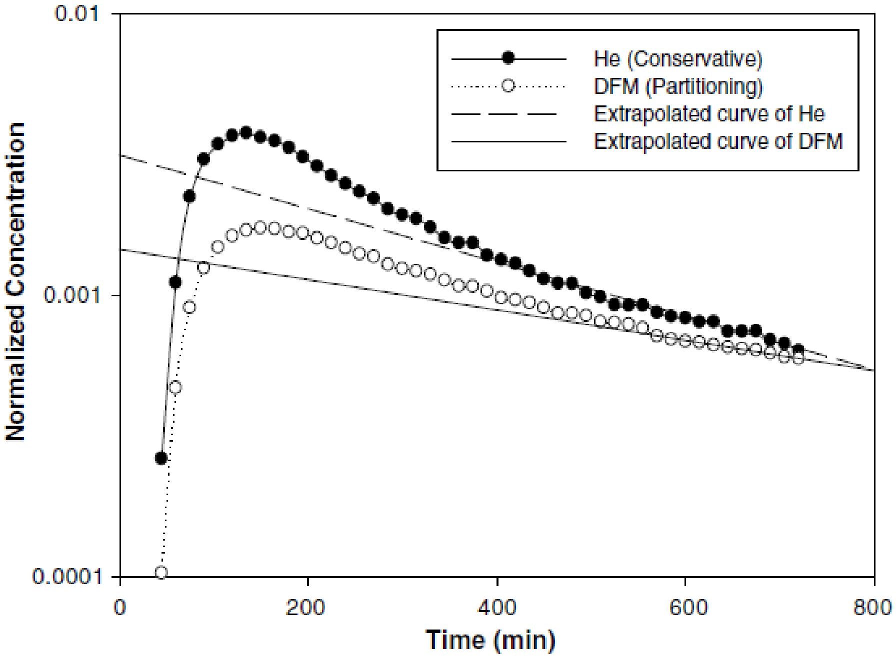


Figure 2.13 Tracer gas concentrations (Imhoff et al., 2007)

A comparison between lysimeter and electrical resistivity tomography (ERT) measurements in in-situ moisture content was conducted by Marcoux et al., (2007) in a bioreactor landfill located in Bouqueval, France. ERT measurements were taken prior to and during leachate recirculation. Results showed that the moisture content increases with time, as shown in Figure 2.14.

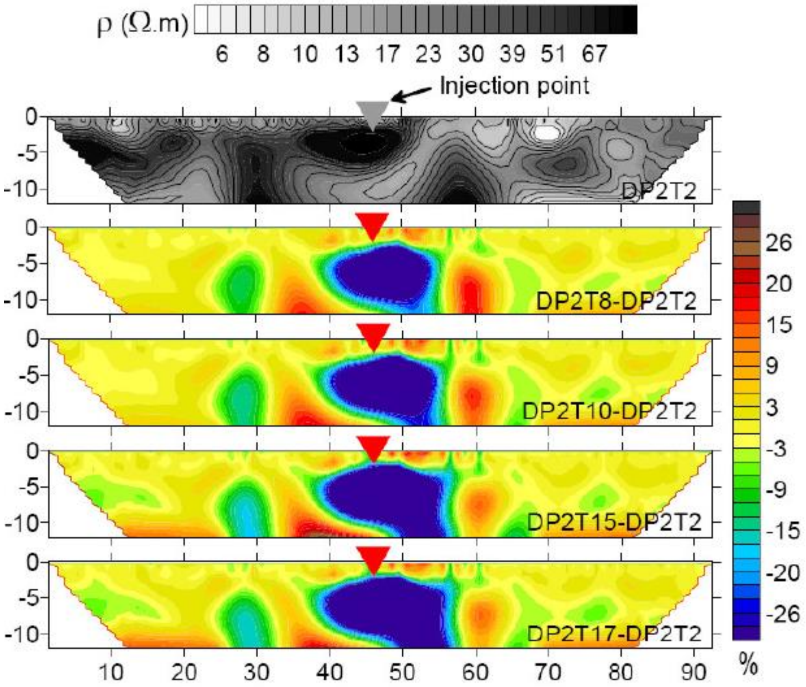


Figure 2.14 Electric resistivity image in a leachate recirculation system (Marcoux et al., 2007)

Catley et al., (2008) performed a field study on the moisture distribution in a bioreactor landfill in Quebec, Canada, using seismic velocity analysis. The objective of the study was to observe the moisture distribution, to determine optimal moisture content, and to map the moisture distribution from the collected seismic data at the surface. The investigators stated that the moisture content increases incrementally with the stacking velocity rate. Figure 2.15 indicates that the stacking velocity increases with time after leachate recirculation.

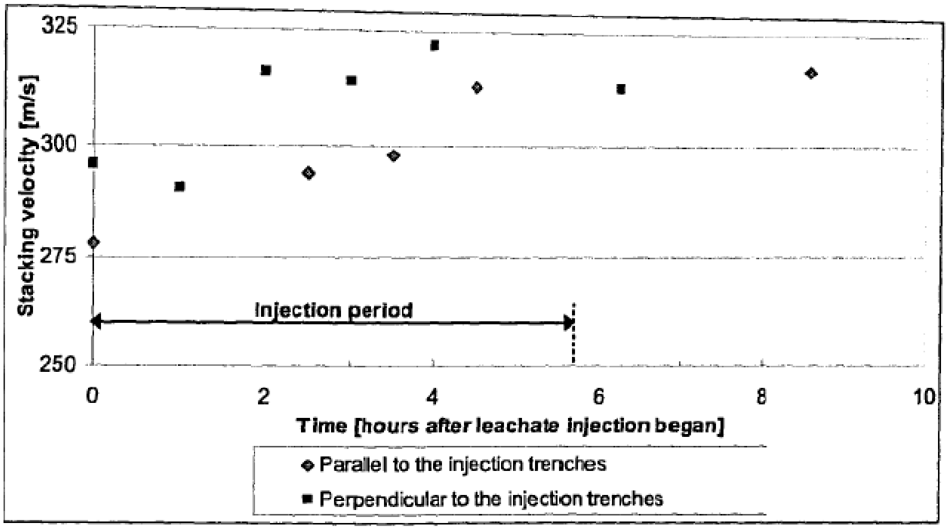


Figure 2.15 Reflection velocities with time conducted parallel and perpendicular to the injection trenches (Catley et al., 2008)

Zhao et al., (2008) examined a full-scale bioreactor landfill, to assess start-up performance under cold weather conditions at Northern Oaks Recycling and Disposal Facility in Harrison, Michigan, USA. They investigated several parameters, including water balance, moisture distribution, leachate characteristics, leachate transport time, settlement, methane and gas concentrations, and temperature variations. The moisture distribution was measured by TDR probes for five different lifts of waste. Figure 2.16 represents the results and indicates that the moisture content increased as leachate was added and redistributed by the injection system.

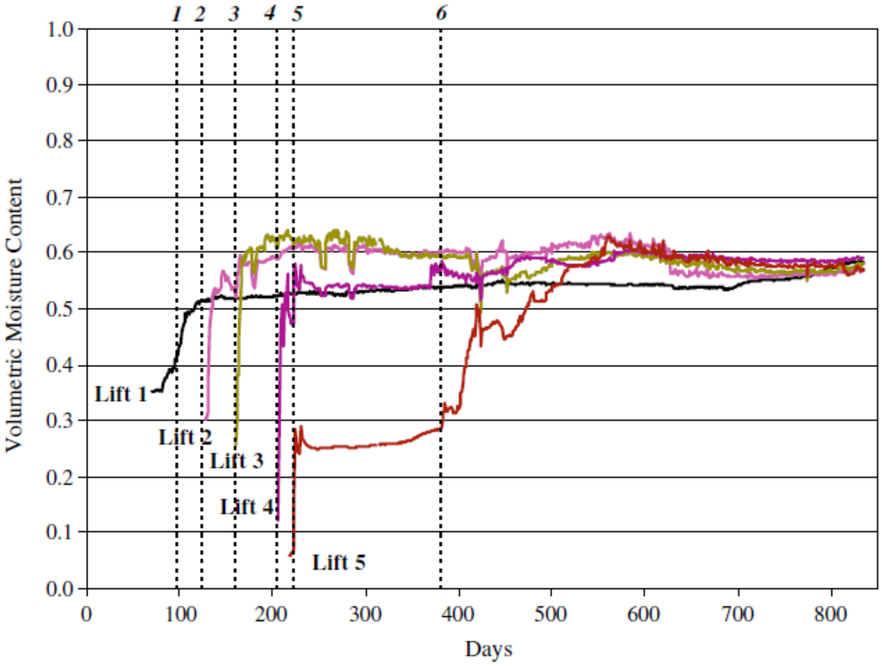


Figure 2.16 The average volumetric moisture contents in each lift with time (Zhao et al., 2008)

Kumar et al., (2009) investigated in situ moisture content at the New River Regional Landfill (NRRL) in Union County, Florida, USA, using resistivity sensors. The moisture variations with time were determined and compared with the gravimetric moisture content of collected samples. The results presented in Figure 2.17 show that the moisture content increased with time after the addition of liquid.

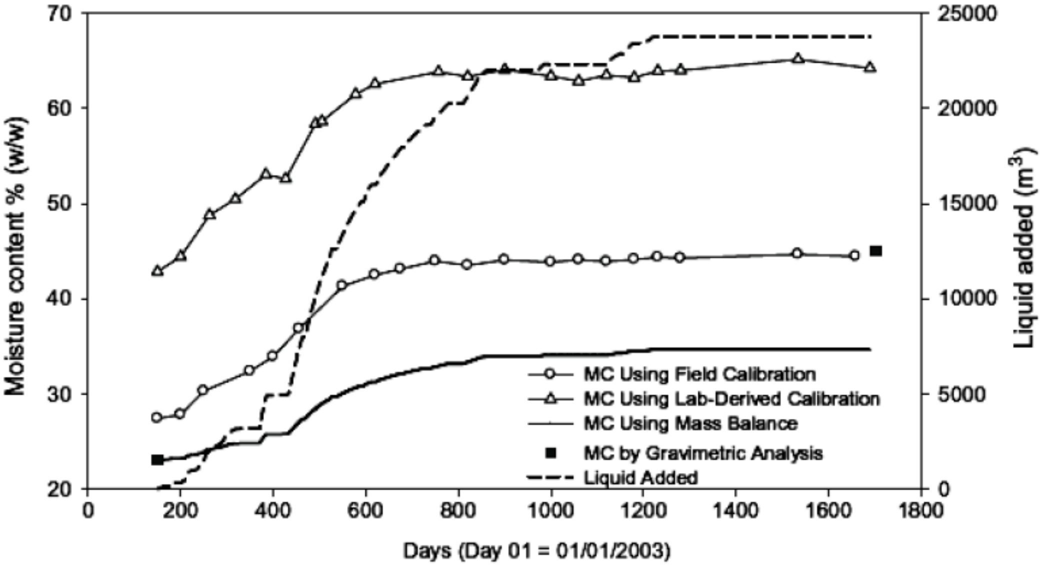


Figure 2.17 Moisture variation measured using sensors (Kumar et al., 2009)

Kadambala et al., (2011) conducted a field study at the New River Regional Landfill (NRRL) in Union County, Florida, USA to investigate pore water pressure, using piezometers. Moisture distribution parameters were determined by using pressure transducers, flow meters, and other instruments. They concluded that pore pressure increases with time after the addition of liquid, as presented in Figure 2.18.

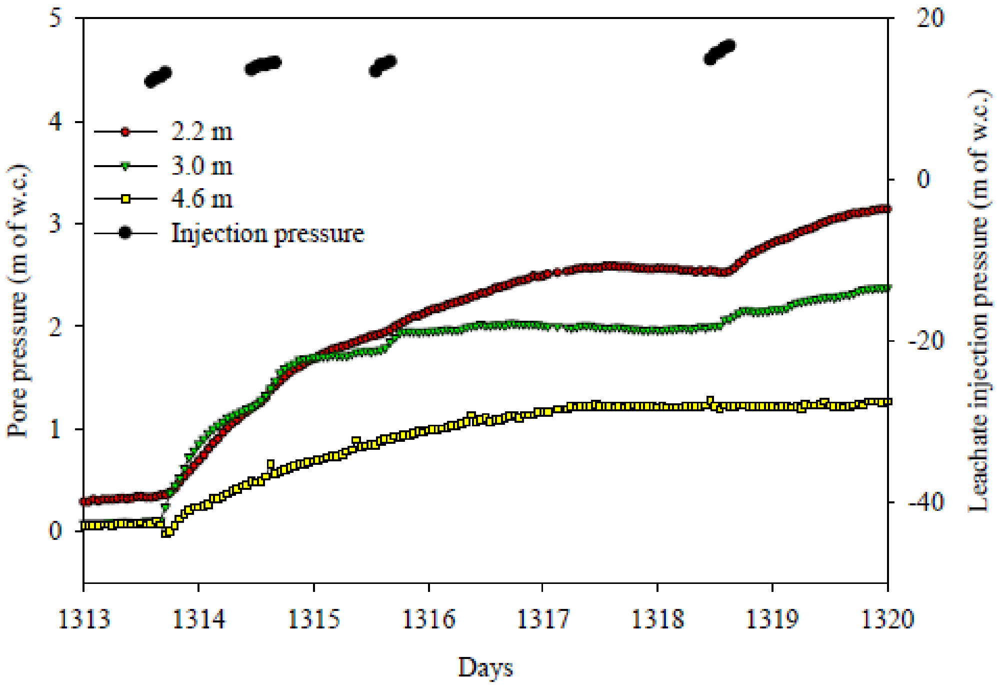


Figure 2.18 Piezometer responses to leachate recirculation with time (Kadambala et al., 2011)

Shihada (2011) performed a lab study to estimate the moisture content of a municipal solid waste landfill, using electrical resistivity imaging. The MSW samples were collected from the City of Denton landfill, Texas. The study concluded that moisture content increases with a decrease in resistivity, as presented in Figure 2.19.

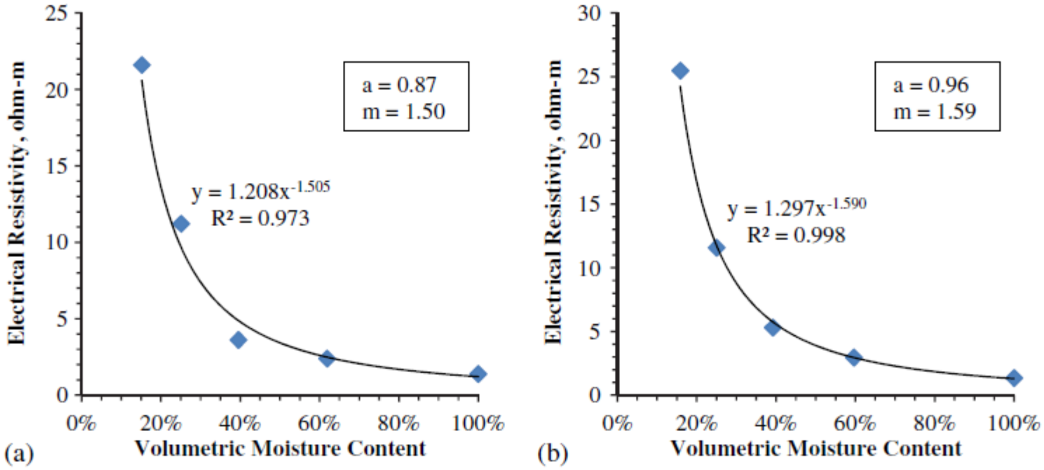


Figure 2.19 Resistivity variation with moisture content for fresh MSW (Shihada et al., 2012)

Yochim et al., (2013) conducted a study to estimate in situ subsurface water content in active landfills, using GPR. Two active landfills, the Region of Waterloo Landfill (RWL) in Waterloo, Ontario and the City of Hamilton Glanbrook Landfill (GL) in Binbrook, Ontario, were utilized to determine moisture variation in landfills. Water content was estimated based on the dielectric permittivity (k) of the landfill waste. The results showed that moisture content varies with the positions of boreholes and the distance between the boreholes, as shown in Figure 2.20.

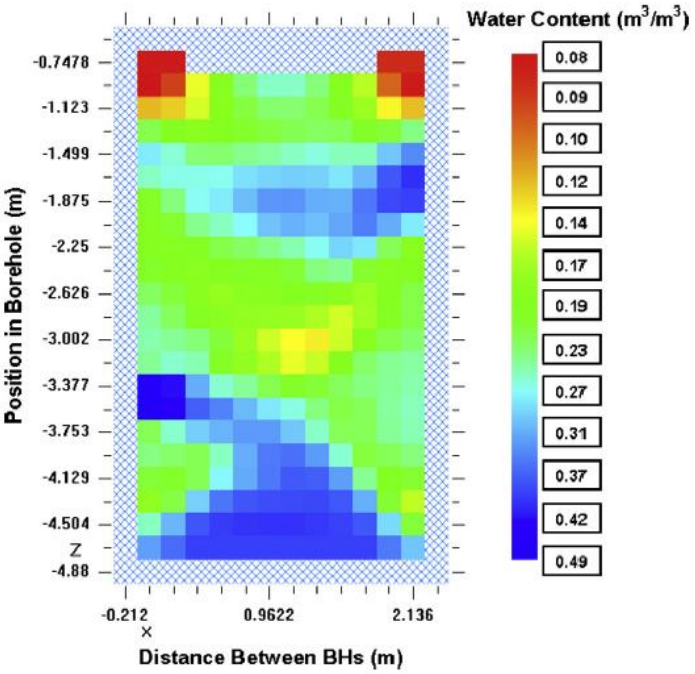


Figure 2.20 Volumetric water content between boreholes (Yichim et al., 2013)

A field investigation was conducted by Manzur et al., (2016) to monitor the extent of moisture variations in a bioreactor landfill, using electrical resistivity imaging. Due to leachate recirculation, 2-D electrical resistivity imaging was performed at the City of Denton landfill, Texas, USA. The results indicate that the moisture content increases with time, as shown in Figure 2.21.

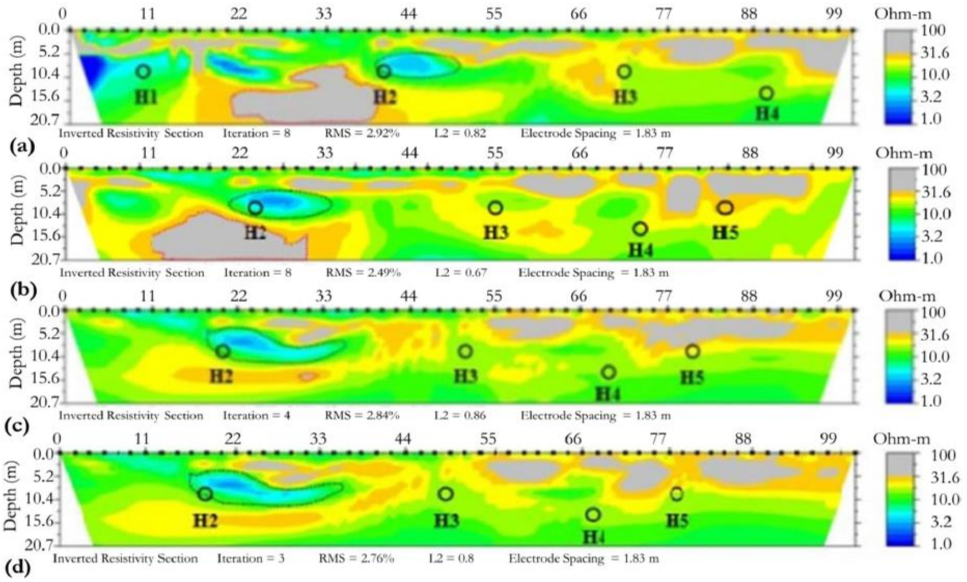


Figure 2.21 Monitoring moisture variations across pipe H2 (a) baseline, (b) 1 day after recirculation of 18,920 L (5006 gallons), (c) 1 day after recirculation of 19,470 L (5151 gallons), (d) 1 day after recirculation of 18,940 L (5010 gallons)

Capelo and deCastro (2007) determined the absolute moisture content and moisture variations of MSW samples collected from the Fortaleza landfill in Brazil. They utilized simulated rain and scattered neurons to observe the absolute moisture content variations in three leaching experiment columns. The observed results and the model proposes that proper simulations would help in understanding the moisture distribution in the experimental columns.

Staub et al., (2010a) applied time domain reflectometry (TDR) to monitor moisture content in landfills by simulating the model in the laboratory. TDR sensitivity depends on the characteristics of MSW, including the composition, density, initial moisture content, moisture distribution, electrical conductivity of fluid, etc. The measurements included the continuous wetting method, sprinkling method, and wetting and compressing the samples to perform the tests. The results showed that the relative volumetric moisture content of MSW depends on apparent travel time. Staub et al., (2010b) studied the long-term moisture distribution in MSW, using leachate recirculation in a large-scale laboratory setup. They collected representative MSW and leachate from a bioreactor landfill in France to perform the study. Scattered neurons and TDR were utilized to measure moisture distribution in the bioreactor cells. The study concluded that after saturating the MSW for 30 days, the moisture accumulates in the bottom of the layers due to gravity.

Mukherjee and Khire (2012) performed a laboratory study on a leachate recirculation system, through a drainage blanket, to monitor moisture distribution in the waste mass. Different amounts of saturated hydraulic conductivity of the MSW and the liquid injection pressure heads were utilized in the study to observe the volumetric moisture content (in terms of degree of saturation) and wetting area. They used pressure transducers and moisture sensors at different levels of the MSW to determine pressure and moisture levels in the landfill. The results, presented in Figure 2.22, indicate that the moisture content varies with time, saturated hydraulic conductivity, and leachate injection rate.

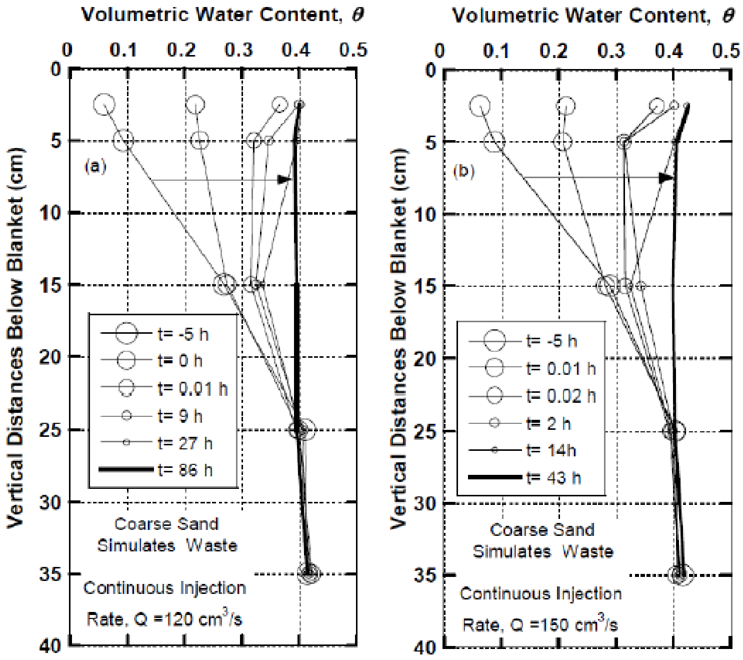


Figure 2.22 Moisture content profiles due to continuous leachate injection (Mukherjee and Khire, 2011)

Factors Affecting Moisture Distribution

Various parameters affect the moisture distribution in a bioreactor landfill, such as the leachate recirculation system, geometric configuration of LRS, composition of MSW, compaction level of the landfill, hydraulic properties of municipal solid waste (MSW), and others.

a) Leachate recirculation system

Leachate recirculation or the addition of water is conducted through a leachate recirculation system which includes horizontal trenches, vertical wells, infiltration blankets, and direct surface application. Horizontal trenches and vertical wells are the most effective ways to inject leachate into the landfill. The application method has transitioned over time and reflects efficient moisture distribution inside the landfill.

b) Geometric Configuration of LRS

   Geometric configuration plays an important role in moisture distribution. In horizontal trenches or vertical wells, spacing and layering are the parameters which most influence moisture distribution.

c) Composition of MSW

   Generally, MSW landfills receive non-hazardous waste from households and industry, and the nature of the waste is heterogeneous. This heterogeneity affects effective moisture distribution by causing preferential paths, etc.

d) Compaction of landfill

   Higher compaction can create ponding inside the landfill, whereas lower compaction may cause slope failure by allowing the added water to flow in a single direction. As a result, the moisture distribution may be inhibited by the compaction level of the landfill.

e) Hydraulic Properties of MSW

   Hydraulic properties, mainly the permeability of MSW, have a significant effect on the moisture distribution of bioreactor landfills.

Effects of Efficient Moisture Distribution

The growth of nutrients and microbes in a bioreactor landfill primarily depends on the addition of water or leachate recirculation. An appropriate environment for this growth occurs when efficient moisture distribution enhances biodegradation of MSW. The effect of uniform and efficient moisture distribution on the enhanced degradation of MSW in bioreactor landfills has been reported by several researchers (Sharma and Reddy, 2004; Reddy, 2006; ITRC, 2006; Reddy et al., 2009). The enhanced degradation process has numerous advantages, such as i) enhancing gas production, ii) improving waste-to-energy generation, iii) accelerating landfill settlement that reduces post-closure monitoring costs, iv) minimizing on-site or off-site leachate treatment costs, v) increasing landfill stabilization, and vi) minimizing the threat to public health and the environment (Kulkarni and Reddy, 2012).

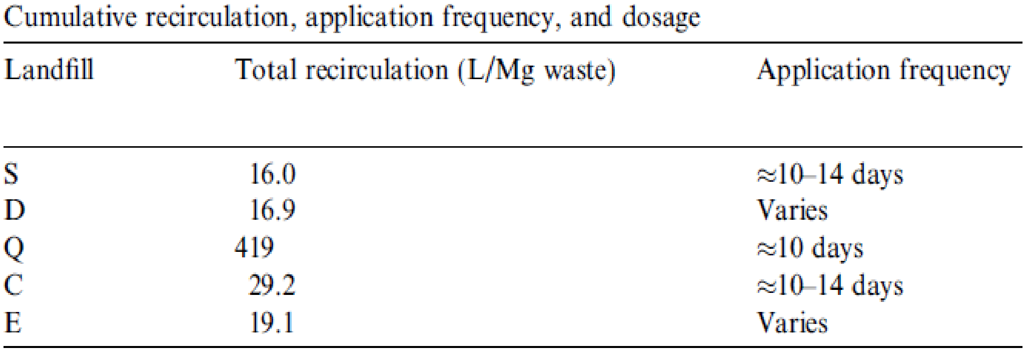
Application Frequency of Leachate

The addition of leachate needs to be studied for its impacts on the economy and the environment. Chan et al., 2002 stated that various problems, such as saturation, ponding, and acidic conditions in landfills, may occur due to a high volume of leachate recirculation. Hence, a minimal quantity of leachate recirculation should be properly adjusted in order to maintain proper landfill operation. Conversely, an increased addition of moisture enhances waste decomposition significantly (Chugh et al., 1998; Christensen, 2012). Thus, leachate application frequency should be selected carefully to maximize waste decomposition without causing significant problems.

Imhoff et al., (2007) conducted a study on state-of-the-art techniques for estimating the amount of moisture needed in landfills. Moisture control is the most critical parameter for a successful bioreactor operation. The rate of biodegradation and waste decomposition can be inhibited by a smaller amount of added liquid. In addition, various problems, such as side seeps, smaller amounts of collected gas, unintended gas leakages, or excessive pore pressures may arise in the landfill from too much water being added. Therefore, the application frequency of leachate recirculation is one of the prime concerns of operating a bioreactor landfill effectively.

Benson et al., (2007) conducted a study of five bioreactor/recirculation landfills to provide the difference between bioreactors/recirculation and conventional landfills in North America, focusing on current practice and technical issues. The application frequency of leachate depended on various factors, such as availability of leachate, level of automation, weather conditions, operational philosophy, and the volume of waste through the recirculation pipe. The application frequency for most of the landfills studied was approximately 10 to 14 days, as presented in Table 2.5. The volume of leachate recirculation was high for only one landfill, Q, while the other four landfills utilized low amounts of recirculation. The relatively low rate of recirculation for most of the landfills indicates that the regulatory prohibition on supplemental liquid addition. The intention of using a higher dose in landfill Q was to optimize waste degradation. The potential change in moisture content depended on the uniform distribution of added supplemental water. Moisture content changed from an initial 15% to approximately 45% (a typical field capacity) due to adequate amounts and frequency of leachate.

Table 2.5 Cumulative recirculation and application frequency



Cumulative recirculation, application frequency, and dosage

Landfill	Total recirculation (L/Mg waste)	Application frequency
S	16.0	≈10–14 days
D	16.9	Varies
Q	419	≈10 days
C	29.2	≈10–14 days
E	19.1	Varies

Bareither et al., (2010) performed a study on leachate hydrology and waste settlement for North American bioreactor landfills. They described that leachate dosing frequency varies from landfill to landfill, based on the operational and management practices. The application frequency was between 8 to 19 days for four of six landfills, as shown in Figure 2.23 and Table 2.6.

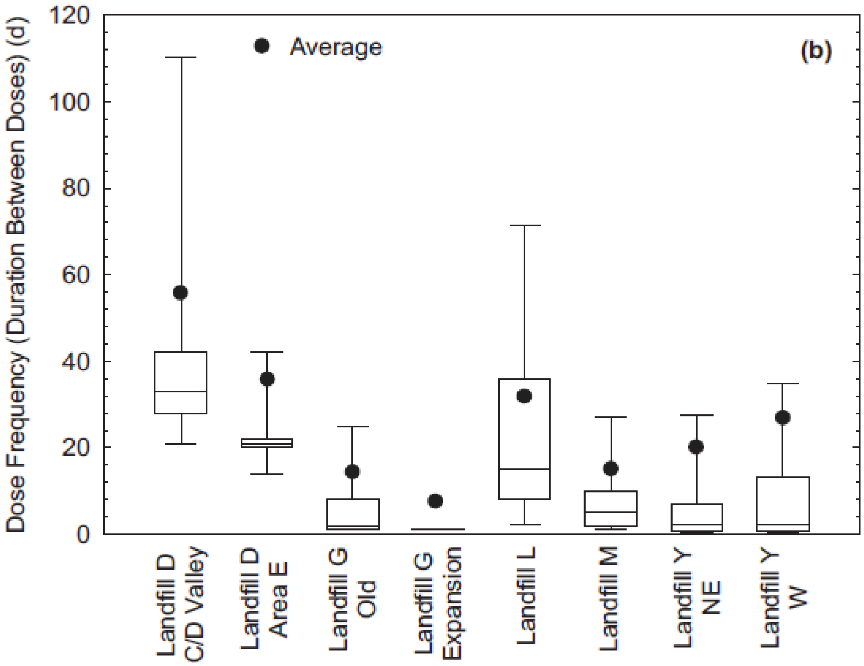


Figure 2.23 Dose frequency for leachate recirculation in horizontal trenches

Table 2.6 Cumulative recirculation and dose frequency

Landfill	Average liquid addition per trench (L/Mg waste)[a]	Average dose (L/m-pipe)	Average duration between doses (days)
D	129	939	45
G-Old	126	604	14
G-Expansion	195	744	8
L	30	198	32
M	318	875	15
Y (NE)	419	178	19
Y (W)	264	269	27

[a] Arithmetic average of the cumulative liquid added per mass of waste for all horizontal trenches at a given landfill.

Monitoring Moisture Distribution in Landfills

The performance of a bioreactor landfill operation depends on the uniform and efficient moisture distribution over time. However, uniform and efficient moisture distribution may not be possible due to the heterogeneity of MSW and non-uniform compaction level. Therefore, monitoring moisture distribution in a landfill is one of the prime concerns for optimizing the effectiveness of a landfill operation. At present, the moisture content of MSW in landfills is determined by using the bucket auger sampling method, boring MSW samples from the landfill, and measuring the moisture content gravimetrically in the laboratory. The current practice of boring MSW samples provides information on moisture content at certain points, but does not represent a general view of moisture variation inside the landfill. Several indirect methods, such as time domain reflectometry (TDR), neutron probes, partitioning gas tracer, electrical resistance sensor, fiber optic sensors, and electrical resistivity tomography were used in the past (Li and Zeiss, 2001; Yuen et al., 2000; Gawande et al., 2003; Imhoff et. al., 2007). The various methods for determining moisture can be summarized as:

a) Time Domain Reflectometry/Transmissometry (TDR/TDT)

Time domain reflectometry (TDR) utilizes the concept of radar, in which a signal is emitted and reflected through the medium or object. The analysis of the reflected signal gives the characteristics of the medium or object, using the relationship between the frequency dependence of the dielectric constant of organic molecules and their molecular structures (Dalton, 1992). Li and Zeiss (2001) conducted a study on the relationship between the volumetric moisture content and the relative permittivity or dielectric constant of the medium. In the TDR method, the volumetric moisture content of the medium is determined by using the developed relationship. The principle of time domain transmissometry (TDT) is similar to TDR, where the time of propagation for an electromagnetic wave along a given length of a transmission line in a medium is measured.

b) Neutron Probe

Neutrons are emitted from a radioactive source and travel through an adjacent and thermalized medium by their collision with the nuclei of other atoms. The neutron thermalizing process is effectively done by hydrogen, as it is the smallest atom. The hydrogen atom content is considered as the proportion of the concentration of thermalized neutrons. As there is no significant additional source of hydrogen atoms in the media without water molecules, the concentration of hydrogen atoms can be related to the moisture within the media. The moisture content of the media can be determined from the measurements by using a suitable calibration curve (Gawande et al., 2003).

c) Capacitance Probe

A capacitance probe is another tool for measuring the moisture content of the medium. In this method, moisture content is measured by using the relationship with the dielectric constant, Ka. Dean et al. (1987) reported that the dielectric constant of water and soil is approximately 80 and 4, respectively, for the same electric field frequencies less than 1000 Mhz. A typical capacitance probe consists one upper and another lower electrode, separated by a plastic dielectric.

d) Electrical Resistance

Moisture content can be determined based on the value of the electrical resistance, which is measured between the electrodes that are inserted into the respective medium. Traditionally, soil moisture content is estimated using electrical resistance sensors consisting of gypsum block sensors or granular matrix sensors (McCann et al., 1992). A method of calibration has been developed for measuring moisture content.

Electrical Resistivity Imaging (ERI)

Introduction

Electrical Resistivity Imaging (ERI) is one of the oldest and most commonly used geophysical techniques in electrical exploration. The Schlumberger brothers first utilized it in 1920. With today's advanced technology, it is used to investigate subsurface conditions, which can be produced with the help of an automated data acquisition system and user-friendly software.

Electrical resistivity depends on different soil properties, such as solid constituents (particle size distribution, mineralogy); arrangement of voids (porosity, pore size distribution, connectivity); degree of water saturation (water content) solute concentration, and temperature. One, two, or three-dimensional surveys are used, depending on the desired end result. In the laboratory, for the calibration of electrical resistivity, one-dimensional arrays are commonly used. Two-dimensional arrays are mainly used to depict the two-dimensional vertical picture of the subsurface soil condition. Various configurations are used in a two-dimensional survey, depending on the respective position of the current and the potential electrodes. For the greater evaluation of anomalies and anisotropies, a three-dimensional survey is used.

Theory of ERI

The process of ERI involves delivering a current to the soil or waste material and resulting potential difference is measured of the sounding medium. Electrical equipotentials are hemispherical in a homogeneous and isotropic half-space, as shown in Figure 2.24 (Scollar et al., 1990; Kearey et al., 2002; Sharma, 1997; Reynolds, 1997).

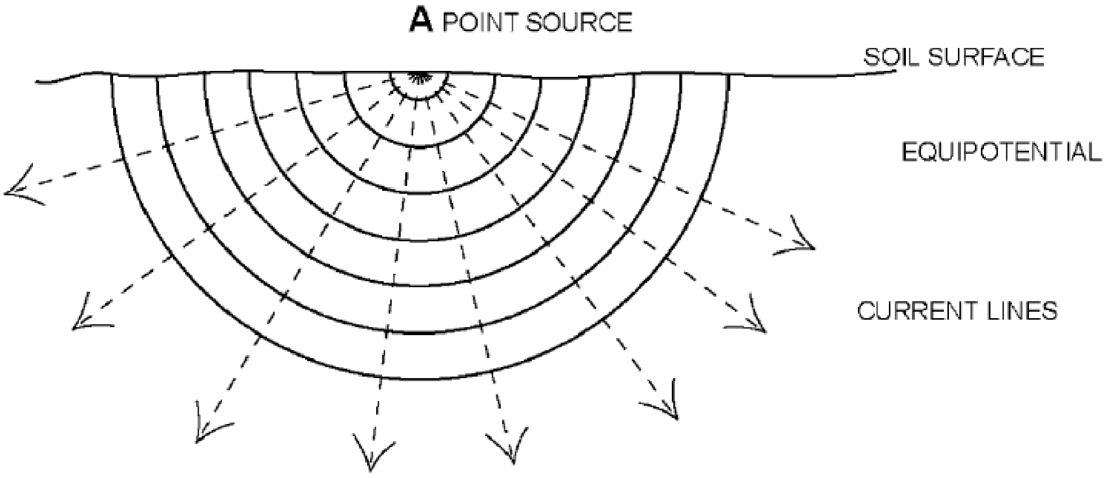


Figure 2.24 Distribution of current flow in a homogeneous Soil

Four electrodes are required to measure electrical resistivity. Electrodes A and B are known as current electrodes, and M and N are recognized as potential electrodes. The current electrodes are used to deliver the current in the soil, and the resulting potential difference is determined by the potential electrodes. The equipotentials and current lines for the pair of current electrodes A and B on a homogeneous half-space are shown in Figure 2.25.

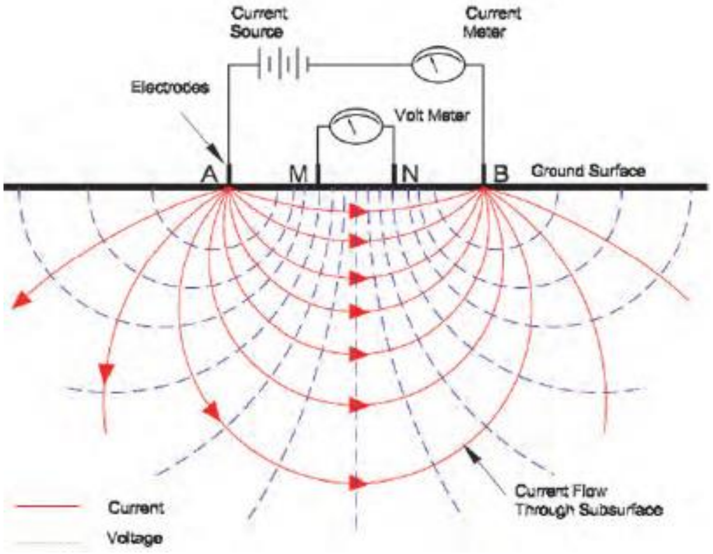


Figure 2.25 Equipotential and current lines for a pair of current electrodes A and B (Muchingami et al., 2013)

Factors Affecting Electrical Resistivity

The ERI method makes it possible to present an “image” of the subsurface. Investigation of hydrogeological, environmental and geotechnical issues have been conducted by using ERI for many years. However, with the development of a new technique for the interpretation of resistivity measurements, 2D resistivity imaging is being frequently used to investigate geophysical and geo-hazard conditions (Hossain et al., 2011). According to Dahlin (2001), ERI is a very popular site investigation and characterization tool for various geotechnical and geo-environmental applications. Several researchers have studied the different affecting factors of the resistivity imaging. The electrical resistivity varies with water content, temperature, ion content, particle size, resistivity of the solid phase, permeability, porosity, and clay content present in the materials (Gueguen and Palciauskas, 1992; Shihada, 2011; Kibria, 2014). The effect of the moisture content on electrical resistivity was studied by several researchers (McCarter, 1984; Michot, 2003; Fukue, 1999; Goyal et al., 1996; Kalinski and Kelly, 1993; Ozcep et al., 2009; and Schwartz and Schreiber 2008). The effect of the degree of saturation (Abu Hassanein et al., 1996), organic content (Ekwue and Bartholomew, 2010), pore water composition (Kalinski and Kelly, 1993) and geologic formation (Giao et al., 2002) was also studied by several researchers.

Another study on the affecting factors of resistivity, conducted by Grellier et al., (2007), focused on how and when the moisture content and temperature highly influence the changes of the resistivity; however, the effects of other parameters on resistivity for the solid waste have not been well established. Guerin (2004) presented that the electrical resistivity of solid waste varies greatly with moisture and temperature. The variations of electrical resistivity of MSW with moisture content, unit weight, stage of decomposition, temperature, composition of MSW, and composition of pore fluid was investigated by Shihada (2011).

Array Configurations of Electrodes

Different types of array configurations are available based on the respective position of current and potential electrodes. The most commonly used array configurations are Wenner, Wenner-Schlumberger, dipole-dipole, pole-pole and pole-dipole that are presented in Figure 2.26.

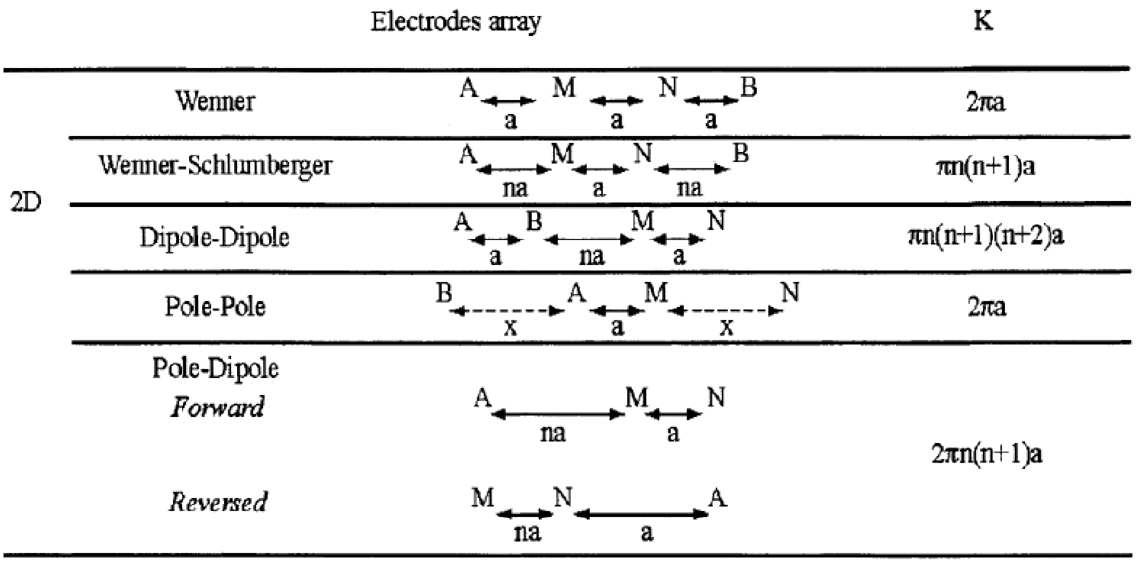


Figure 2.26 Different array configuration for 2D resistivity imaging (Samouëlian et al., 2005)

Samouelian et al., (2005) described the array configurations as having significant influence on the resolution, sensitivity, and depth of investigation. Table 2.7 represents the summary of the sensitivity of the array to horizontal and vertical heterogeneities, depth of investigation, horizontal data coverage, and signal strength.

Table 2.7 Characteristics of different 2D array configurations

	Wenner	Wenner-Schlumberger	Dipole-Dipole	Pole-Pole	Pole-Dipole
Sensitivity of the array horizontal structures	++++	++	+	++	++
Sensitivity of the array vertical structures	+	++	++++	++	+
Depth of investigation	+	++	+++	++++	+++
Horizontal Data Coverage	+	++	+++	++++	+++
Signal Strength	++++	+++	+	++++	++

The labels are classified form (+) to (++++), equivalent at poor sensitivity to high sensitivity for the different array configurations.

Application of RI in MSW Landfill

Recently, resistivity has been one of the primary techniques used in determining the electrical resistive properties of soil. An accurate interpretation of the subsurface geologic setting can be made based on the distributed resistivity profile (Maganti, 2008). ERI is a non-invasive geophysical technique which is used for surface exploration, subsurface characterization, and monitoring. A multichannel electrical resistivity investigation has simple physical principles and an efficient data acquisition, making it a popular method today. According to several studies, ERI can be used in different applications, such as determination of unknown foundation depth, evaluation of moisture content in landfills, determination of foundation failures, detection of sinkholes, detection of soil cracking, evaluation of underground water, etc.

Several literature studies are available for better understanding of the effect of leachate recirculation in bioreactor landfills (Rosqvist et al., 2005, Grellier et al., 2007, 2008; Moreau et al., 2003; Guerin et al., 2004; Clement et al., 2010). A study was performed by Hossain et al., (2010) to conduct moisture movement within an ELR/bioreactor landfill by using electrical resistivity imaging. 2D electrical resistivity imaging was performed to measure the moisture distribution at the City of Denton landfill (Manzur, 2013).

The purpose of resistivity imaging in landfills is to measure moisture content, moisture distribution or variation, moisture movement, and moisture extent. Guerin et al., (2004) utilized RI to monitor moisture distribution. Manzur et al., (2016) used RI for the extent of moisture movement in bioreactor landfills. The moisture variation was investigated by Griller et al., (2006), using RI at Orchard Hills landfill (Illinois, USA). Marcoux et al., (2007) performed a study using RI to observe moisture variations in landfill. Shihada (2011) developed an equation to determine moisture content of MSW, using RI.

Water Balance of Bioreactor Landfill

The general concept of water balance in a bioreactor landfill defines water or liquid input (into the landfill) as equal to the summation of water or liquid output and water or liquid storage inside the landfill. Several researchers describe water balance by using the following equation.

$$L = P+J-R_{off} -AET-U_w$$

Where

P = Precipitation

R_{off} = Runoff

U_w = Soil moisture storage

L = Lateral drainage

J = Leachate recirculation

AET = Actual evapotranspiration.

Water balance of landfill final cover was studied by Albright et al., (2004) where 11 field sites in the United States were used to estimate the field waste balance. Local or on-site soils were primarily used to make the final covers, and the slopes of the landfills were maintained at 5% to 25%, depending on the site condition. The results showed that the value of surface runoff ranged from 0.0 to 10.2% of precipitation and had an average value of 3.8%, which was nearly free from the influence of the slope of the cover, the type of cover, and the climate. The value of lateral drainage ranged from 0.0 to 5% of precipitation and had an average value 2.0%, which was a small fraction of the water balance. For the conventional covers with composite barrier, the average value of percolation rates were less than 12mm/yr. and 1.5mm/yr. at humid, arid, semiarid, and sub-humid locations, respectively. For alternative covers, the average value of percolation rates ranged between 33 to 160 mm/yr. and less than 2.2mm/yr. in humid climates and arid, semiarid, and sub-humid climates, respectively.

Khire et al., (1997) performed a study to compare the field and measured data of water balance of earthen final covers by using HELP and UNSAT-H software. The components' overland flow, soil water storage, evapotranspiration, and percolation were measured and compared in this study. The predicted value of soil water storage by numerical modeling was lower than the measured soil water storage, where the effect of frozen ground surface was ignored. Municipal solid waste landfill was taken into consideration to conduct the water balance of a dry and a wet landfill in Melbourne, Australia (Yuen et al., 2001). A neutron probe, weather station, real-time logger, and some other things were set up to measure the hydrological data. It was assumed that an equal amount of leachate drains to maintain moisture equilibrium after adding water. However, effective moisture retention capacity was expected to be a lower value. For the pre-capping, 20% of the rainfall evaporated, 54% was absorbed in the waste mass, and the remaining 26% percolated through the waste mass. Surface runoff was negligible, and volumetric moisture content increased from 20% to 27%. For the post-capping, this situation was totally different, where the evaporation percentage was relatively higher. Volumetric moisture content increased from 27% to 31% as it was capped.

Components of Water balance

Precipitation

Precipitation is the first and foremost component of water balance in landfill. At the start of a precipitation event, water is stored in depressions or as snow, or is lost to evapotranspiration or plant interception. Surface runoff will generate if the rate of precipitation is greater than the rate of infiltration plus evaporation, or if the ground surface is frozen. The discretization of the precipitation affects the water balance in landfills.

Runoff

Generally, simulated and measured runoff are always different in value, as there has not been good agreement of them. Scanlon et al., (2002) reported that certain models underestimated runoff for evapotranspirative cover systems at certain sites, while other researchers reported the opposite (Roesler et al., 2002).

Infiltration

Infiltration is the process by which water can enter into the soil profile. The influence of matric potential, gravity gradients, and the instantaneous infiltration rate or infiltrability leads water to move into the soil at the beginning. Water penetrates the soil as fast as it arrives if the rate of water delivery to the soil surface is smaller than the soil’s infiltrability, which eventually eliminates runoff. If interception and runoff are overestimated, infiltration is underestimated, and vice versa.

Storage

A portion of the water infiltrated into the soil profile may be stored in the soil matrix, and the remaining portions are used by evapotranspiration, lateral drainage, or vertical drainage. Water storage in the soil matrix is a complex process, as the soil matric potential and water content relationship is hysteretic. Water content is higher in drying conditions than in wetting conditions for a given matric potential.

Evapotranspiration

Evapotranspiration is a combination of the evaporation of water stored on the soil surface, intercepted by plants, and transpiration by plants. In general, evaporation and transpiration are difficult to separate, as they are interdependent processes that are often lumped together. The atmospheric vapor pressure increases and the rate of evapotranspiration decreases if water evaporates from a surface under the energy provided by solar radiation and ambient air temperature. Evapotranspiration proceeds until a water vapor pressure gradient if present.

Available Computer Models for Water Balance

Water balance in landfills can be simulated by using a number of available computer models. Most water balance models were developed to evaluate water flow in the vadose zone, or for agricultural modeling. According to Gross (2005), the following water balance models are utilized for research purposes:

- EPIC
- HELP
- HYDRUS-ID,

- LEACHM
- SHAW
- SWIM
- UNSAT-H,
- VS2DT

The major water balance processes are considered by all of these models except for interception and vapor flow, which are only conceived by and significant for a few models and in certain cases. All of the models have been used for a long time to simulate the hydraulic performance of evapotranspirative cover systems.

Selection of Computer Models for Performing Water Balance

Based on the characteristics and the past use of these models to evaluate evapotranspirative cover systems, HELP, was utilized to conduct the analysis. HELP is the most common and frequently-used computer model for water balance and cover system design of landfills. For example, New York employed it for water balance, and New Mexico, for cover system design. A number of water balance studies are available that have compared the predicted water balance for evapotranspirative cover systems using various software and HELP. For this study, Visual HELP, an updated and different version of HELP, was selected to perform water balance.

Visual HELP is the most recently-developed hydrological model for designing landfills, predicting leachate mounding, and evaluating potential leachate contamination. The program has an easy-use interface and powerful graphical features, with the latest version of HELP model (v.3.07) built in to assist in designing the model and evaluating the modeling results. The program provides user-friendly interface and flexible data-handling procedures, having both the basic and advanced features of the HELP model for designing landfills. The program also includes an International Weather Generator to create synthetic data of daily precipitation, air temperature, and solar radiation up to 100 years, and a database of soil, waste, and geomembranes that contains properties of 42 common landfill materials (www.waterloohydrogeologic.com).

Visual HELP Model Input Parameters

The input parameters for Visual HELP were determined by laboratory and field tests, as well as by obtaining expert opinions of other researchers to simulate the forward model. The program has default and user- specified values for most of the input parameters. The Visual HELP program includes the site location (nearest city); weather data (daily precipitation, temperature, and solar radiation); evapotranspiration data (LAI, evaporative zone depth, and growing season); soil data (total porosity, field capacity, wilting point, saturated hydraulic conductivity, and initial moisture contents); runoff data (Scs runoff curve information, slope and slope length); installation information about geosynthetics used, if any (i.e., installation quality and number of defects in geomembrane); and a cover profile description (depth of layer, type of layer such as barrier or vertical percolation layer).

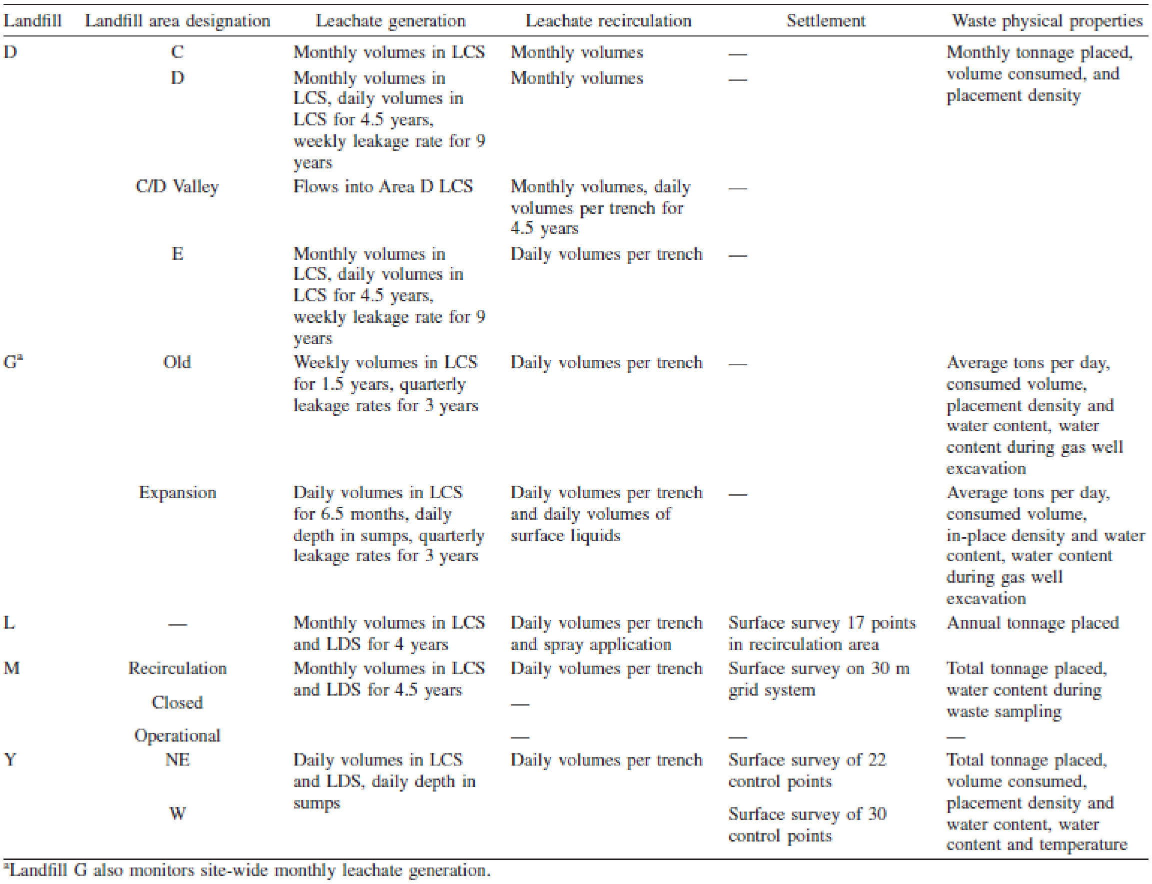
Performance of Bioreactor Landfill

The performance of a bioreactor landfill depends on the design of the leachate collection system, variable quality of the injected leachate, and the short monitoring time (Bureau et al. 2005). In addition, numerous influential factors, including slope stability, liner and final cover integrity, landfill gas production and emission and landfill settlement, and water balance affect the performance of landfill (EPA Report, September, Louisville, Kentucky, 2006; Morris and Barlaz, 2011; Bareither et. al. 2010; EPA Report, Cincinnati, Ohio, August, 2005; Bureau et al., 2005).

Performance Indicators of Bioreactor Landfill

Performance of the landfill is affected by several factors that attain the efficiency of landfill. Landfills are frequently considered for urban development, but have limitations due to problems associated with the differential settlements, leachate generation, and gas emissions. Among all the practical problems, settlement may be the most crucial problem of utilizing landfill sites for development (Sowers 1973, Morris and Woods, 1990). Most of the global MSW is dumped in non-regulated landfills, and the generated methane is emitted to the atmosphere. Part of the methane generated in landfills can be captured and used as a renewable energy source. As mentioned earlier, modern landfills try to collect the biogas produced by anaerobic digestion. Decomposition of organics provides the source of gas production in landfills, and decomposition products are the primary constituents of landfill gas. The nature of MSW and the stage of decomposition determine the landfill gas composition. The potential of landfill gas production depends on the components of the MSW. Monitoring data are the key variables to characterizing a landfill's performance. Bareither et al., (2010) mentioned that the monitoring of most landfills is conducted for regulatory compliance or to assess use of air space. The study also presented the performance indicators, which were monitored over time, and are shown in Table 2.8.

Table 2.8 Landfill performance indicators



Landfill	Landfill area designation	Leachate generation	Leachate recirculation	Settlement	Waste physical properties
D	C	Monthly volumes in LCS	Monthly volumes	—	Monthly tonnage placed, volume consumed, and placement density
	D	Monthly volumes in LCS, daily volumes in LCS for 4.5 years, weekly leakage rate for 9 years	Monthly volumes	—	
	C/D Valley	Flows into Area D LCS	Monthly volumes, daily volumes per trench for 4.5 years	—	
	E	Monthly volumes in LCS, daily volumes in LCS for 4.5 years, weekly leakage rate for 9 years	Daily volumes per trench	—	
G[a]	Old	Weekly volumes in LCS for 1.5 years, quarterly leakage rates for 3 years	Daily volumes per trench	—	Average tons per day, consumed volume, placement density and water content, water content during gas well excavation
	Expansion	Daily volumes in LCS for 6.5 months, daily depth in sumps, quarterly leakage rates for 3 years	Daily volumes per trench and daily volumes of surface liquids	—	Average tons per day, consumed volume, in-place density and water content, water content during gas well excavation
L	—	Monthly volumes in LCS and LDS for 4 years	Daily volumes per trench and spray application	Surface survey 17 points in recirculation area	Annual tonnage placed
M	Recirculation	Monthly volumes in LCS and LDS for 4.5 years	Daily volumes per trench	Surface survey on 30 m grid system	Total tonnage placed, water content during waste sampling
	Closed		—		
	Operational		—	—	—
Y	NE	Daily volumes in LCS and LDS, daily depth in sumps	Daily volumes per trench	Surface survey of 22 control points	Total tonnage placed, volume consumed, placement density and water content, water content and temperature
	W			Surface survey of 30 control points	

[a] Landfill G also monitors site-wide monthly leachate generation.

Landfill Settlement and Additional Space Gain

Landfill settlement is necessary for the application of post-closure final cover, and is one of the major concerns of landfill management. Several adverse effects, such as surface ponding, crack development, and cover system failure may occur due to large post-closure settlement. Ling et al., (1998) observed 30%-40% settlement over long periods of time. Landfill settlement is associated with waste volume reduction, in which the compression of waste occurs due to self-weight, overburden pressure, external loads, and waste decomposition. Landfill settlement, mechanism, and after effects were studied by several researchers (Merz and Stone, 1962; Rao et al., 1977; Sowers, 1973; Dodt et al., 1987; and

Coduto and Huitric, 1990). Morris and Wood (1990) concluded that high overburden pressure, due to the effect of the cover, causes more settlement.

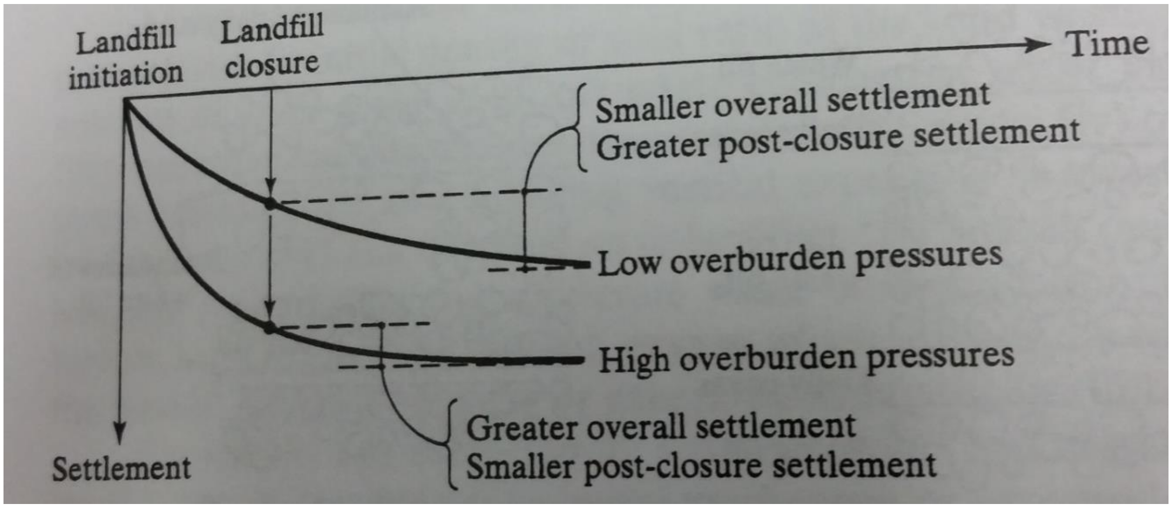
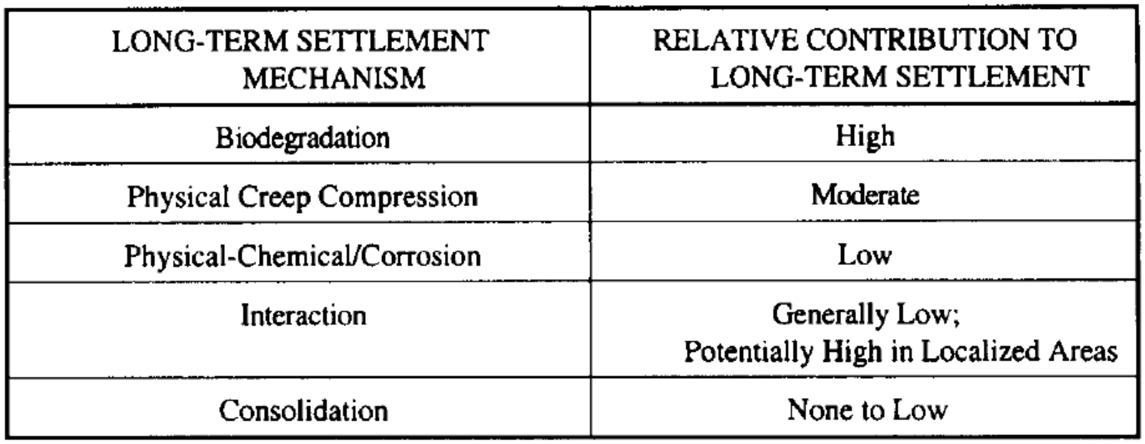


Figure 2.27 Possible settlement curves for dense and light fills

Landfill settlement affects the protection design system such as covers, barriers, and drains. Excessive settlement may have adverse effects by creating ponding and fracture of covers and drains. This may cause an increased amount of leachate entering the landfill, and it produces more leachate. As earlier discussed, the settlement of landfill starts immediately after placing the solid waste in it, and continues over a long period of time. The mechanism of landfill settlement is more complex than that of soil because of the extreme heterogeneity of waste and the presence of large voids. According to Sowers (1973), Murphy and Gilbert (1985), Edil et al., (1990), and Edgers et al., (1992), the main mechanisms involved are a) mechanical compression, b) raveling, c) physical-chemical change, and d) bio-chemical decomposition.

Leonard et al., (2000) presented mechanisms that cause large and small settlements. Large settlements are mainly caused due to mechanical/primary compression, biodegradation, and physical creep compression that includes raveling/void filling. Small settlements occur due to physical-chemical corrosion, interaction, and consolidation. The study also presented a summary of long-term settlement mechanisms and their relative contributions, as depicted in Table 2.9.

Table 2.9 Summary of long-term settlements mechanisms and their relative Contribution.



LONG-TERM SETTLEMENT MECHANISM	RELATIVE CONTRIBUTION TO LONG-TERM SETTLEMENT
Biodegradation	High
Physical Creep Compression	Moderate
Physical-Chemical/Corrosion	Low
Interaction	Generally Low; Potentially High in Localized Areas
Consolidation	None to Low

Settlement of waste is irregular in nature, and a large settlement occurs within one or two months after construction. Furthermore, the settlement continues, due to secondary compression, over a long period of time. Figure 2.28 presents the landfill settlement over an extended period of time.

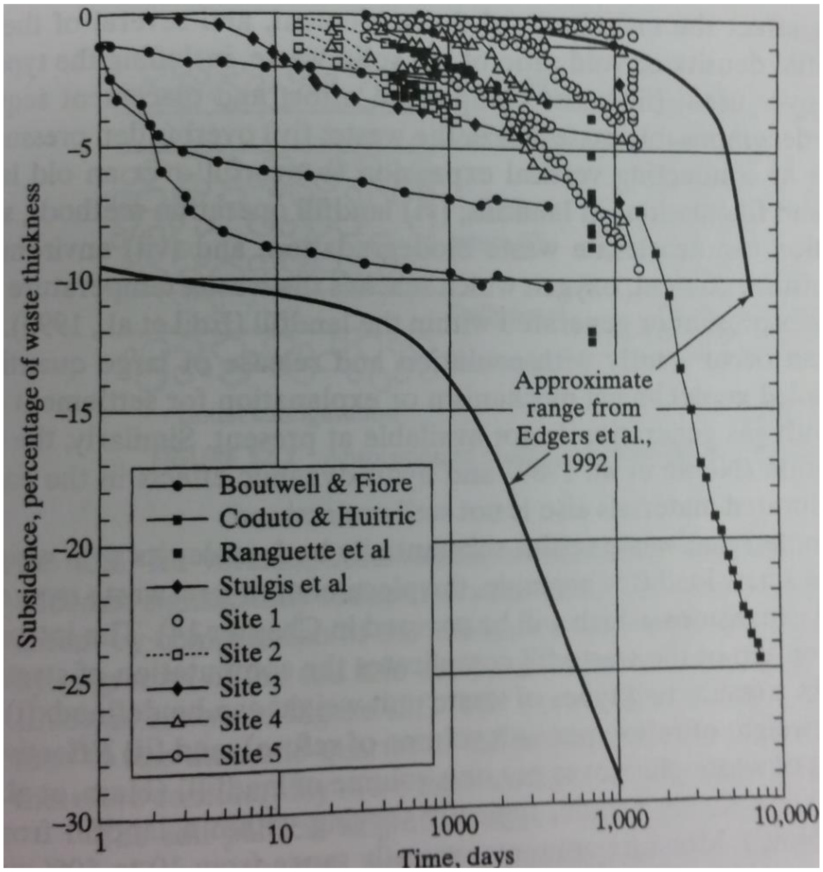


Figure 2.28 Landfill subsidence, new and previously published data (after Spikula, 1997)

Factors Affecting Landfill Settlement

Landfill settlement is affected by several factors, such as a) void ratio; b) initial density; c) types and amount of daily cover; d) compaction effort; e) waste placement sequence; f) decomposable materials present in the waste; g) overburden pressure; h) stress history; i) leachate amount, level, and fluctuations; j) operation methods of landfill that include leachate recirculation; k) environmental factors such as the presence of moisture content, temperature, oxygen, and gas (Edil et al. 1990). Fei and Zekkos (2012) explained the effect of affecting factors on landfill settlement. According to their study, the affecting factors are external vertical stress, aeration, waste composition, and total unit weight.

Effects of Landfill Settlement: Additional Space Gain

Landfill settlement may have some disadvantages, but the optimum design and controlled operation may turn waste settlement into a big advantage. The magnitude of settlement decreases over a long period of time. Edil et al., (1990) concluded that most of the waste settlement occurs within the first year or first two years, and ranges from 5 to 30% of the original thickness that happens under its self-weight. A study conducted by Mehta et al., (2002), on refuse decomposition due to leachate recirculation at the Yolo County Landfill, California, US, stated that the waste settlement that occurs in a bioreactor is approximately 12% faster than in the control cell, which is operated as a conventional landfill. The comparison is presented in Figure 2.29.

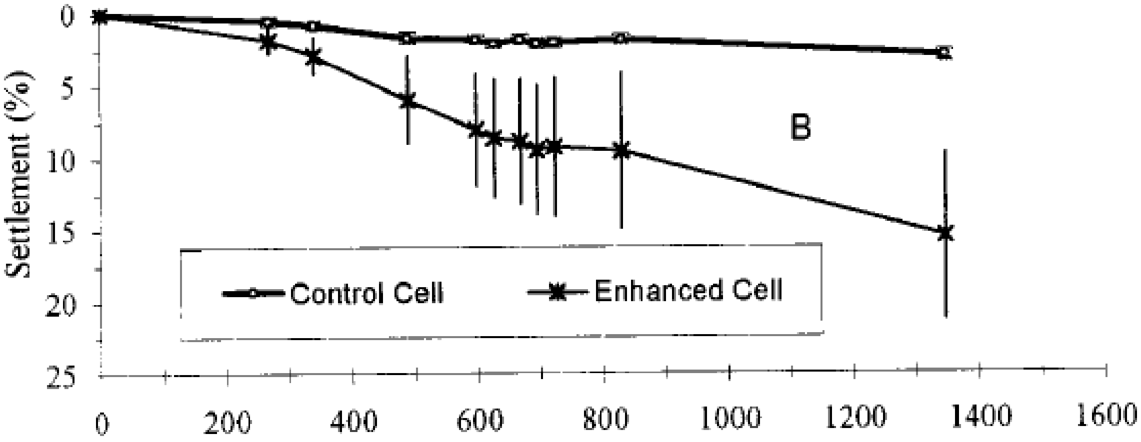


Figure 2.29 Refuse settlement over time

One of the major advantages of landfill settlement is additional space gain. Due to long-term settlement over time, air space increases, which can then be filled with additional waste.

A study at Yolo County Central Landfill (YCCL, 1997), California showed that 14 inches of additional space was gained in one year by increased settling in a bioreactor landfill. The benefit of the additional space gain is that the air space can be utilized for the placement of new solid waste, thereby earning the owner of the landfill more money. Another important benefit is that it minimizes the usage of new land for landfill operations. An assumed cost analysis indicates the benefits of the additional space gain. A schematic diagram of additional space gain due to landfill settlement is presented in Figure 2.30.

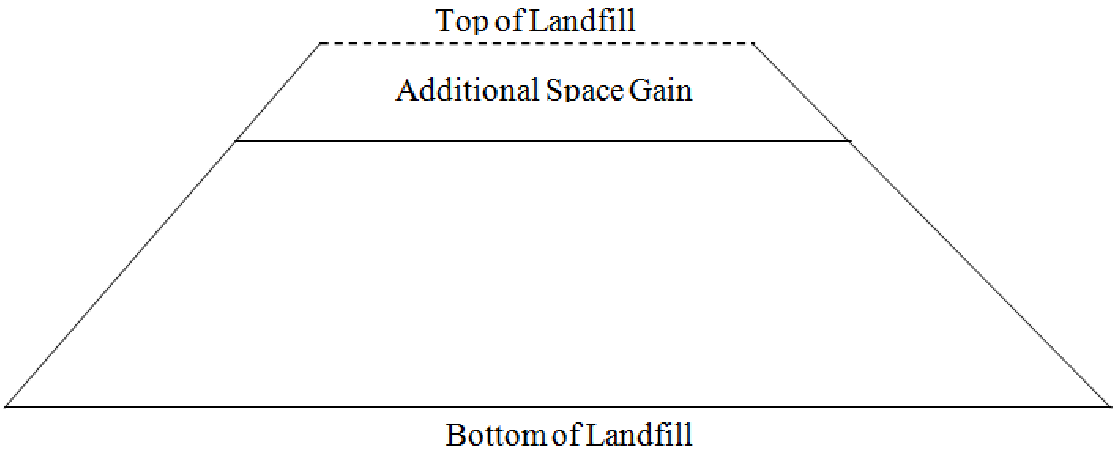


Figure 2.30 Schematic diagram of landfill settlement and additional space gain.

Landfill Gas Production and Energy Generation

In general, landfill gas generation is a function of waste decomposition. Landfill gas generation consists of four different phases, as illustrated in Figure 2.31 (US EPA, 1997). Phase I is the aerobic phase, in which oxygen is consumed for CO2 production. This continues until the available oxygen is depleted. In this stage, no methane is generated, and the produced gas is mainly CO2 and N2. The aerobic decomposition may take place within 6 to 18 months, depending on the waste placement at the landfill (EMCON, 1998).

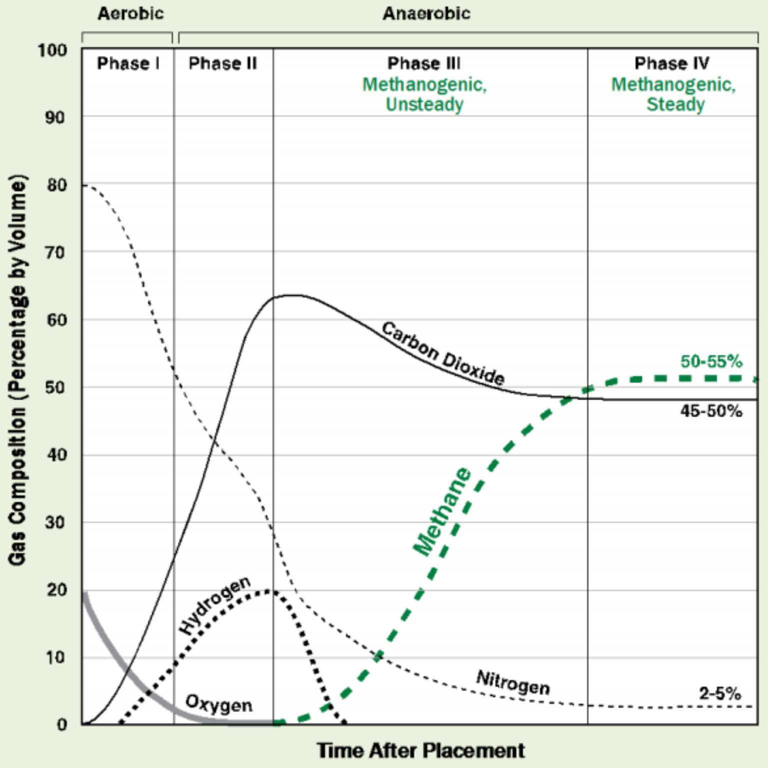
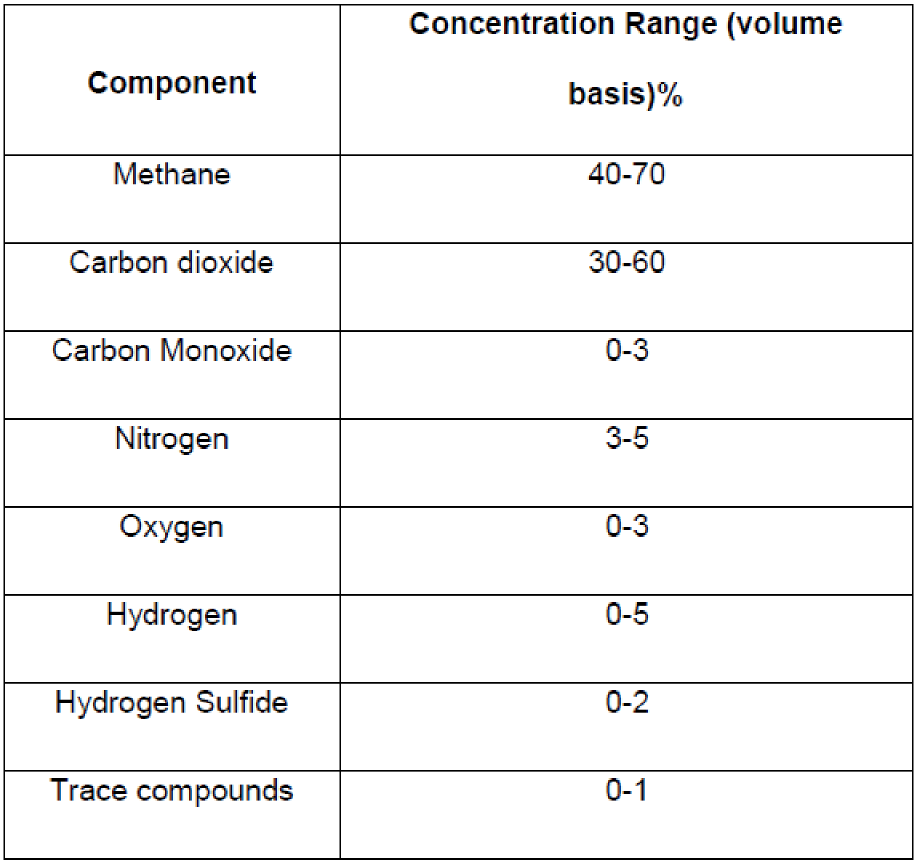


Figure 2.31 Changes in landfill gas generation phases (US EPA, 1997)

Phase II decomposition begins just after the consumption of oxygen is completed. In this anaerobic acid stage, a little methane is generated at the end of the phase, while the gas produced is still mainly CO_2. Phase III is called the accelerated methane generation stage, where the methane generation rate increases, the pH increases, carboxylic acid concentration decreases, and the methane generation reaches 50-60%. Then Phase IV starts, in which the methane generation rate decreases, but the concentration of methane and carbon dioxide remains 60% and 40%, respectively, as in Phase III. Methane and carbon dioxide are the primary components of landfill gas. A study by Yesiller et al., (2008) presented that waste heterogeneity, landfill operation, and environmental conditions play an important role in the variability of gas generation. The typical constituents of MSW landfill gas are listed in Table 2.10.

Table 2.10 Typical constituents of landfill gas (El-Fadel et al., 1997)



Component	**Concentration Range (volume basis)%**
Methane	40-70
Carbon dioxide	30-60
Carbon Monoxide	0-3
Nitrogen	3-5
Oxygen	0-3
Hydrogen	0-5
Hydrogen Sulfide	0-2
Trace compounds	0-1

Factors Affecting Gas Generation

Composition of Waste

Most municipal solid waste, i.e., residential and commercial, placed in landfills is decomposable. The other remaining non-degradable parts consist of various inert materials such as concrete, ash, soil, plastics, and metals. MSW composition plays an important role in decomposition of solid waste, including the time required for it to decompose. A higher percentage of organic waste in the landfill increases the rate of gas generation.

Waste Moisture Content

The moisture content of waste is the one of the most important factors that affects gas generation. The production rate of gas increases with the increment of available moisture (Christensen and Kjeldsen, 1989). Moisture content in a landfill changes due to the addition of liquid, i.e., precipitation, surface water infiltration, seasonal variations, and release water, as result of waste decomposition. Optimum gas generation generally depends on the optimum moisture content.

Particle Size of Waste

The particle size of waste plays an important role: the smaller particle size, the larger the specific surface area. A large surface area can hold more moisture and results in faster decomposition. As a result, if a landfill uses shredded waste materials, the overall decomposition rate will be faster and more gas will be generated. A study conducted by Agdog and Sponza (2005) on shredded waste materials found that the percentage of methane generation was higher for shredded materials.

Age of Waste

Landfill gas generation begins immediately after the placement of waste, but the percentage of methane is very small. With time, waste decomposition increases, and more gas is produced. Methane production in landfills has two primary time-dependent variables: lag time and conversion time. The lag time begins when waste is placed in the landfill and ends when methane generation begins, which is at the beginning of Phase III.

Conversion time is the period of time from waste placement to the end of methane generation, which is the end of Phase IV.

Temperature

Temperature has significant influence on the microbial growth that enhances waste decomposition. The optimum temperature for mesophilic bacteria is 30 to 35°C (86 to 95°F). According to EMCON's (1980, 1981) study, the typical range of landfill gas temperature is 30 to 40C (86 to 140F). Optimum temperatures are reported from 30 to 40°C (86 to 104°F). Methanogenic activity decreases below 15C (59° F) (Mcbean et al., 1995). Zhu Xiang-rong et al., (2002) conducted a study on the geotechnical behavior of the MSW in the Tianziling landfill, and reported that the temperature of the boring was between 30 to 46°C. A range of temperature from 25 to 40C was presented in the study of refuse decomposition in the presence and absence of leachate recirculation (Mehta et al., 2002).

Leachate Recirculation

Leachate recirculation is associated with a bioreactor landfill operation, and accelerates waste decomposition by providing additional moisture. Gas generation is enhanced due to enhanced waste decomposition. Mehta et al., (2002) conducted a study on refuse decomposition in the presence and absence of leachate recirculation and reported that the methane generation rate is higher in an enhanced cell than in a control cell. Leachate recirculation was present in the enhanced cell, but no leachate was recirculated in the control cell.

Other Factors

Several other factors that have influence on landfill gas generation include pH, nutrient content, bacterial content, oxidation-reduction potential, density of gas production, waste compaction, landfill dimensions (area and depth), and the landfill operations (Fungaroli and Steiner, 1979; McBean et al., 1995).

Gas Generation rate

The landfill gas generation rate can be defined as the total volume of gas that is generated in a specific period of time. Qian et al., (2002) presented a range-of-gas generation rate from 0.04 ft^3 ($2.5m^3$) LFG/ lb. waste/yr. to 0.14 ft^3 (8.74 m^3) LFG/ lb. waste/ yr. On the basis of empirical evidence, the gas generation rate was suggested at or below 0.10 ft^3 (6.24 m^3) LFG/ lb. waste/yr. for most of the landfills. Two different tests were conducted by Themelis and Ulloa (2007), and the maximum methane generation rate observed was 1.3 ml CH_4/day-day gm, as presented in Figure 2.32. The methane generation rate was reported as a range from 0 to 90 Nm^3/min for a landfill receiving 286,000 tons waste/yr. (Barlaz et al. 2002). Themelis and Verma (2004) reported methane generation rates from 73 to 135 Nm^3 per ton of dry biomass.

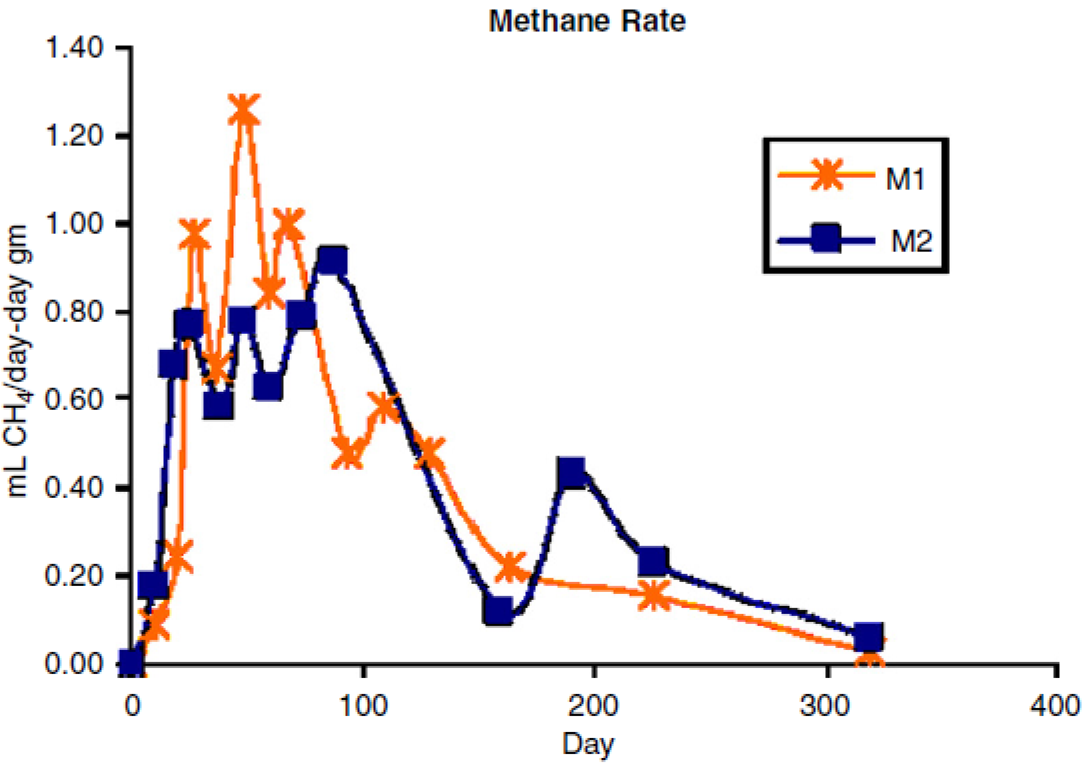


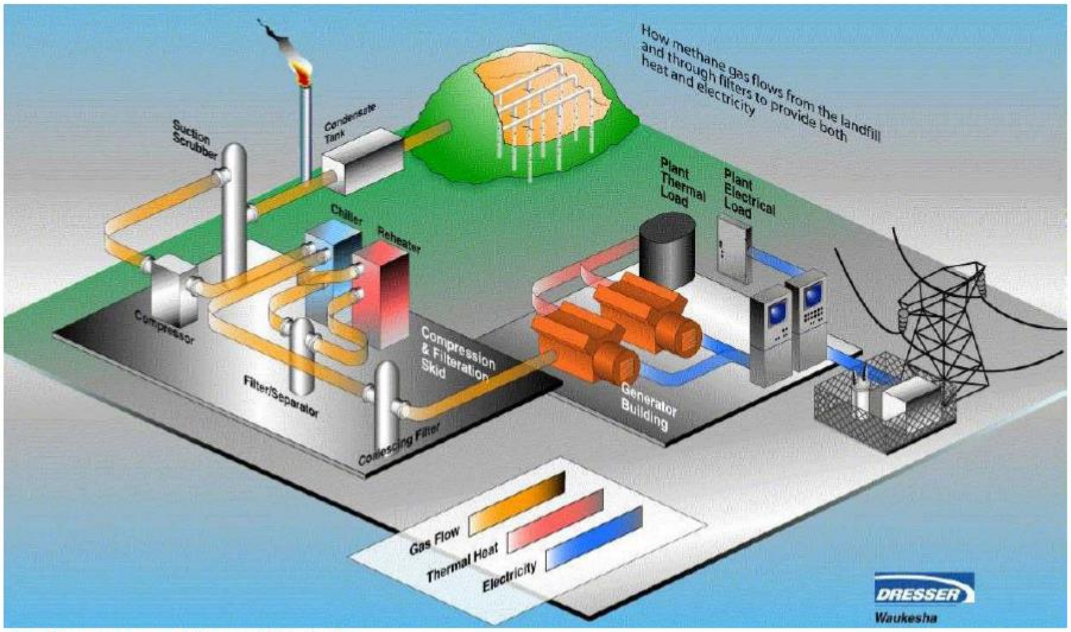
Figure 2.32 Generation of methane in experimental apparatus simulating landfill bioreactors (M1 and M2 denote two different tests)

Utilization of Generated Gas: Gas to Energy

Landfill gas (LFG) is a natural byproduct of the chemical and biological processes occurring in landfilled waste. The main constituents of LFG are methane (50-60%) and carbon dioxide (40-50%). There were 551 active LFGTE projects in the US in April 2011, and the design electricity production capacity was 1700 MW annually. The US EPA estimates that there are an additional 510 candidate landfills in the US that could feasibly operate a LFGTE project (US EPA LMOP, 2011). The Orange County Florida project earns $400,000 per year for rights to the LFG. This project also reduces methane emissions by almost 30,000 tons per year, which improves environmental quality (US EPA LMOP, 2008). Orange County directly benefits both financially and environmentally by the project. The City of Albany, NY landfill was studied by R.S Lynch & Company, Inc., and it was reported that they operate a 33,000 MWh LFGTE plant. The landfill can potentially receive annual carbon values of over $1.6 million in carbon offset credits, over $1.5 million in RECs, and over $0.3 million in PTCs for a duration of 10 years (Lynch, 2008). A typical US landfill disposing of 459 million tons of waste annually can produce 500,000 kWh of electricity. Based on the average electricity price per kWh, the landfill can earn a huge amount of money.

The LFG project has several advantages, which include a) reducing greenhouse gases, b) improving global climate change, c) minimizing the use of non-renewable resources, d) improving local air quality, e) increasing landfill revenue, f) reducing energy costs for users of LFG energy, and d) the creation of more jobs. US LMOP (2014) conducted a study on LFG energy potential of 636 projects and estimated electricity generation of 16 billion kWh, as presented in Figure 2.33. The study also estimated the revenue from LFG project, as shown in Table 2.11. Figure 2.34 presents a typical LFG-to-energy project diagram that includes LFG collection, treatment system, and energy recovery system generation for both electricity and heat.

Figure 2.33 Estimated LFG energy project output in the United States (July 2014)



Graphic courtesy of Dresser Waukesha

Figure 2.34 LFG collection, treatment, and energy recovery

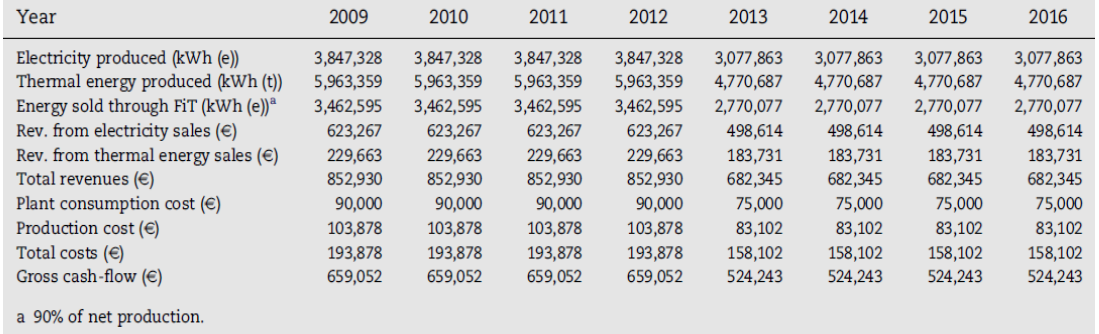
Table 2.11 Revenue creation (2014)

Economic Benefits	Typical 3 MW LFG electricity project	Typical Direct Use Project (1,040 scfm)	
		5-mile pipeline	10-mile pipeline
New project expenditures for the purchase of generators, and gas compression, treatment skid and auxiliary equipment	$1.5 million	$1.1 million	$2.2 million
Increase in state-wide economic output	$4.1 million	$2.8 million	$5.2 million

MW: megawatt scfm: standard cubic feet per minute

An Italian case study was conducted by Caresana et al., (2011) on energy production from landfill gas and provided data which is useful for similar cases. The energy production and economic analysis are presented in Table 2.12, as follows.

Table 2.12 Energy produced and economic results of the cogeneration plant with one internal combustion engine (Caresana et al., 2011)



Year	2009	2010	2011	2012	2013	2014	2015	2016
Electricity produced (kWh (e))	3,847,328	3,847,328	3,847,328	3,847,328	3,077,863	3,077,863	3,077,863	3,077,863
Thermal energy produced (kWh (t))	5,963,359	5,963,359	5,963,359	5,963,359	4,770,687	4,770,687	4,770,687	4,770,687
Energy sold through FiT (kWh (e))[a]	3,462,595	3,462,595	3,462,595	3,462,595	2,770,077	2,770,077	2,770,077	2,770,077
Rev. from electricity sales (€)	623,267	623,267	623,267	623,267	498,614	498,614	498,614	498,614
Rev. from thermal energy sales (€)	229,663	229,663	229,663	229,663	183,731	183,731	183,731	183,731
Total revenues (€)	852,930	852,930	852,930	852,930	682,345	682,345	682,345	682,345
Plant consumption cost (€)	90,000	90,000	90,000	90,000	75,000	75,000	75,000	75,000
Production cost (€)	103,878	103,878	103,878	103,878	83,102	83,102	83,102	83,102
Total costs (€)	193,878	193,878	193,878	193,878	158,102	158,102	158,102	158,102
Gross cash-flow (€)	659,052	659,052	659,052	659,052	524,243	524,243	524,243	524,243

a 90% of net production.

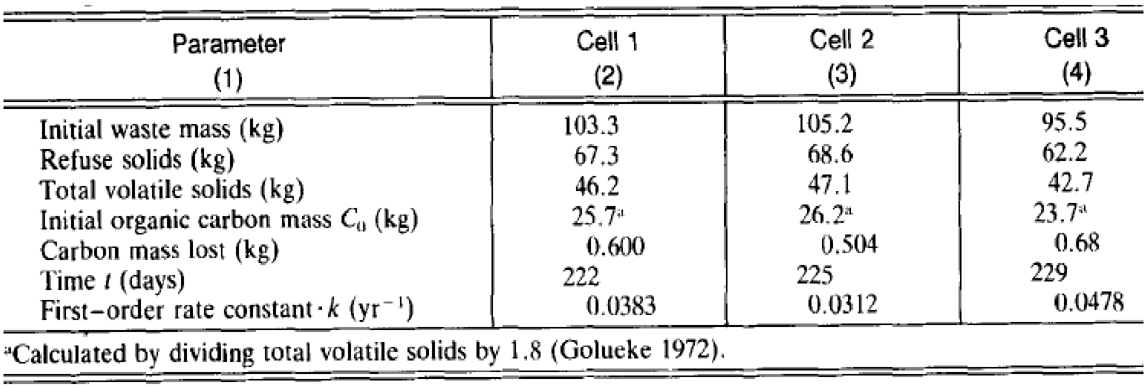
Zamorano et al., (2007) performed a study on the energy potential of an urban waste landfill in southern Spain. They observed overall gas flow rates ranges from 250 to 550 Nm^3/h, which has the potential to generate as much as 4,500,000 kWh/year of electricity.

Landfill Waste Decomposition and Stabilization

According to Barlaz et al., (1990), the refuse of landfill typically contains 40-50% cellulose, 10-15% lignin, 12% hemicellulose, and 4% protein on a dry-weight basis. The study also stated that 91% of the methane potential depends on the cellulose plus hemicelluse fraction of the refuse. In most of the well-decomposed landfills, the percentage of cellulose concentrations was found to be 8-30% (Bookter and Ham, 1982). A study was conducted by Barlaz et al., (1989) on a lysimeter and observed that the mineralization of 71% of cellulose and 77% of hemicellulose occurred within 111 days. The study concluded that the availability of municipal refuse for biological decomposition is approximately 25-40%.

Wall and Zeiss (1995) performed a study on municipal landfill biodegradation and settlement to account for the ability of biological decomposition to reduce the amount of time needed to reach biological stabilization of the waste to non-degradable matter. They observed that the value of leachate total organic carbon (TOC) decreased from initial values of 19,000-25,000 mg/L to 18,000-20,000 mg/L after 225 days. The pH value increased from initial values of 4.0-4.7 to 5.8-6.6 with the addition of a buffer. The total amount of gas volume generation increased to over 800 L/cell. The other findings observed in the study are presented in Table 2.13, as follows.

Table 2.13 Parameters due to waste decomposition



Parameter (1)	Cell 1 (2)	Cell 2 (3)	Cell 3 (4)
Initial waste mass (kg)	103.3	105.2	95.5
Refuse solids (kg)	67.3	68.6	62.2
Total volatile solids (kg)	46.2	47.1	42.7
Initial organic carbon mass C_0 (kg)	25.7[a]	26.2[a]	23.7[a]
Carbon mass lost (kg)	0.600	0.504	0.68
Time t (days)	222	225	229
First-order rate constant $\cdot k$ (yr^{-1})	0.0383	0.0312	0.0478

[a]Calculated by dividing total volatile solids by 1.8 (Golueke 1972).

Another study was conducted by Erses et al., (2008) on the comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. Landfill gas generation increased with time due to waste decomposition. The observed result is presented in Figure 2.35.

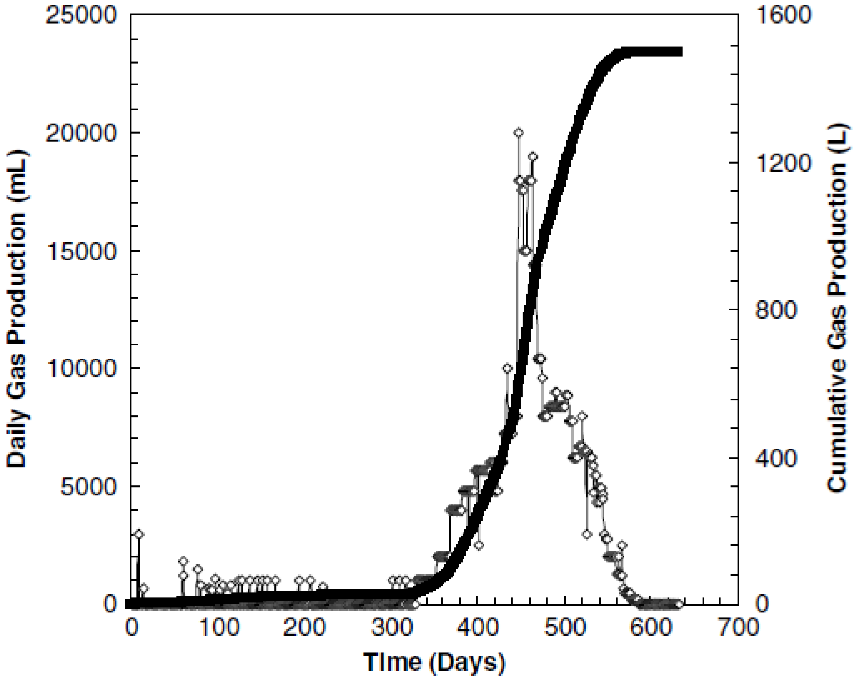


Figure 2.35 Daily and cumulative gas production due to waste decomposition (Erses et al., 2008)

Mechanism of Waste Decomposition

Due to the microbial activity, decomposition of organic components/biodegradable portions of solid waste begins after the placement of waste into the landfills. Several studies describe the decomposition process of landfilled organic materials (Chen et al., 2008; Hattori, 2008; Barlaz et al., 2010; Khalid et al., 2011). Methane and carbon dioxide are the main components generated in the landfill as a byproduct of the waste degradation. The natural organic compounds near the surface of the landfill are oxidized aerobically with the presence of atmospheric oxygen. Based on the above studies, there are mainly three steps found that take place in anaerobic digestion.

The first step is that the complex organic matters are hydrolyzed into soluble molecules by the fermentative bacteria. In the second step, acid-forming bacteria converts the molecules into simple organic acids, carbon dioxide, and hydrogen. The principal acids produced are acetic acid, propionic acid, butric acid, and ethanol. In the last step, the methanogenic bacteria breaks the acids down to methane and carbon dioxide. The representative reactions of methane formation can be shown as:

Acetogenesis $C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$

Methanogenesis $CH_3COOH \rightarrow CH_4 + CO$

$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$

The maximum amount of methane or natural gas that may be generated during anaerobic decomposition of cellulose can be shown by the following equations:

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$$

$$C_6H_{10}O_4 + 1.5\ H_2O \rightarrow 3.25\ CH_4 + 2.75\ CO_2$$

Li et al. (2011) described a process flow of methane generation on the basis of their study on solid-state anaerobic digestion for methane production from organic waste, as presented in Figure 2.36, as follows.

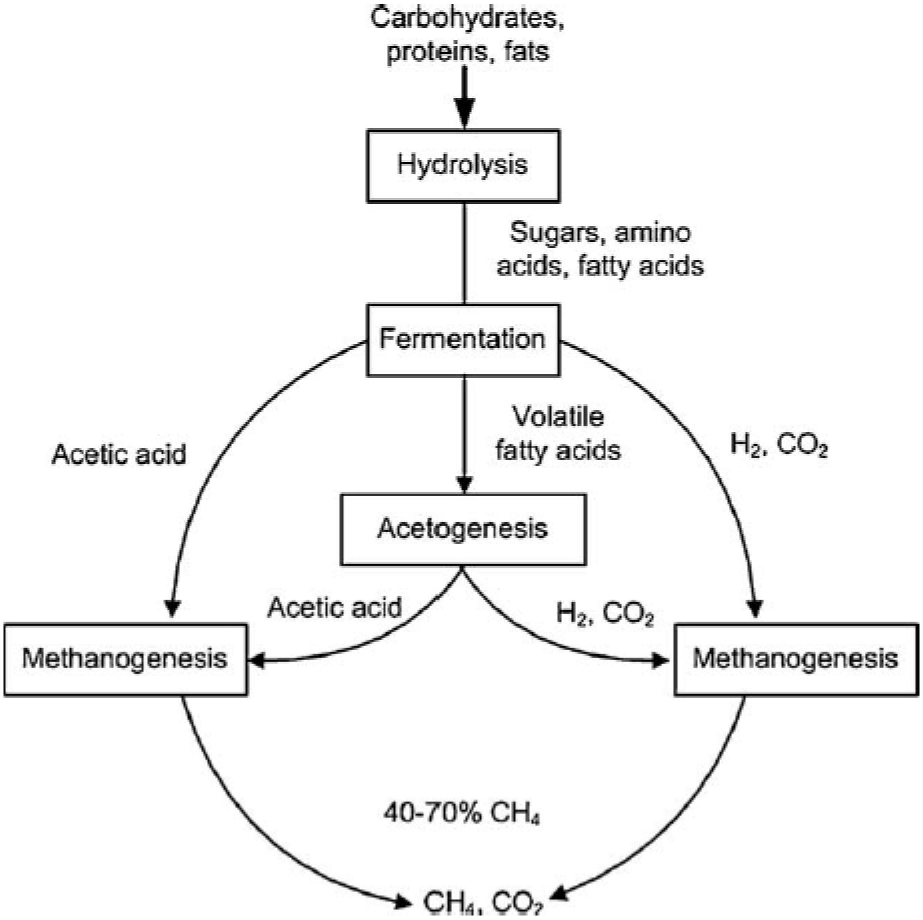


Figure 2.36 Process flow of the degradation of organic material through anaerobic digestion.

Factors Affecting Waste Decomposition

Several parameters affect the biodegradation of landfill waste, including moisture content, pH, alkalinity, temperature, nutrients, absence of toxins, particle size, and oxidation-reduction potential.

i) Moisture content

Moisture content is the one of the main factors that affects MSW decomposition. Increased moisture content accelerates the biodegradation process of the landfilled waste.

This is a fundamental and governing concept for the effective operation of bioreactor landfills. Researchers (Pohland, 1986 and Rees, 1980) observed that the optimum moisture content for rapid waste decomposition and increased gas generation can be considered 60%.

ii) pH

A pH range from 6 to 8 is considered ideal for waste decomposition to produce methane from the landfilled waste (Ehrig, 1983). A pH value of less than 5 creates acidic conditions, which cause the inhibition of microbial activities and thus affect waste degradation.

iii) Alkalinity

Optimum alkalinity is necessary for the waste decomposition process methanogenesis. Farquhar and Rovers (1973) reported an optimum alkalinity value of 2000 mg/L for methanogenesis.

iv) Temperature

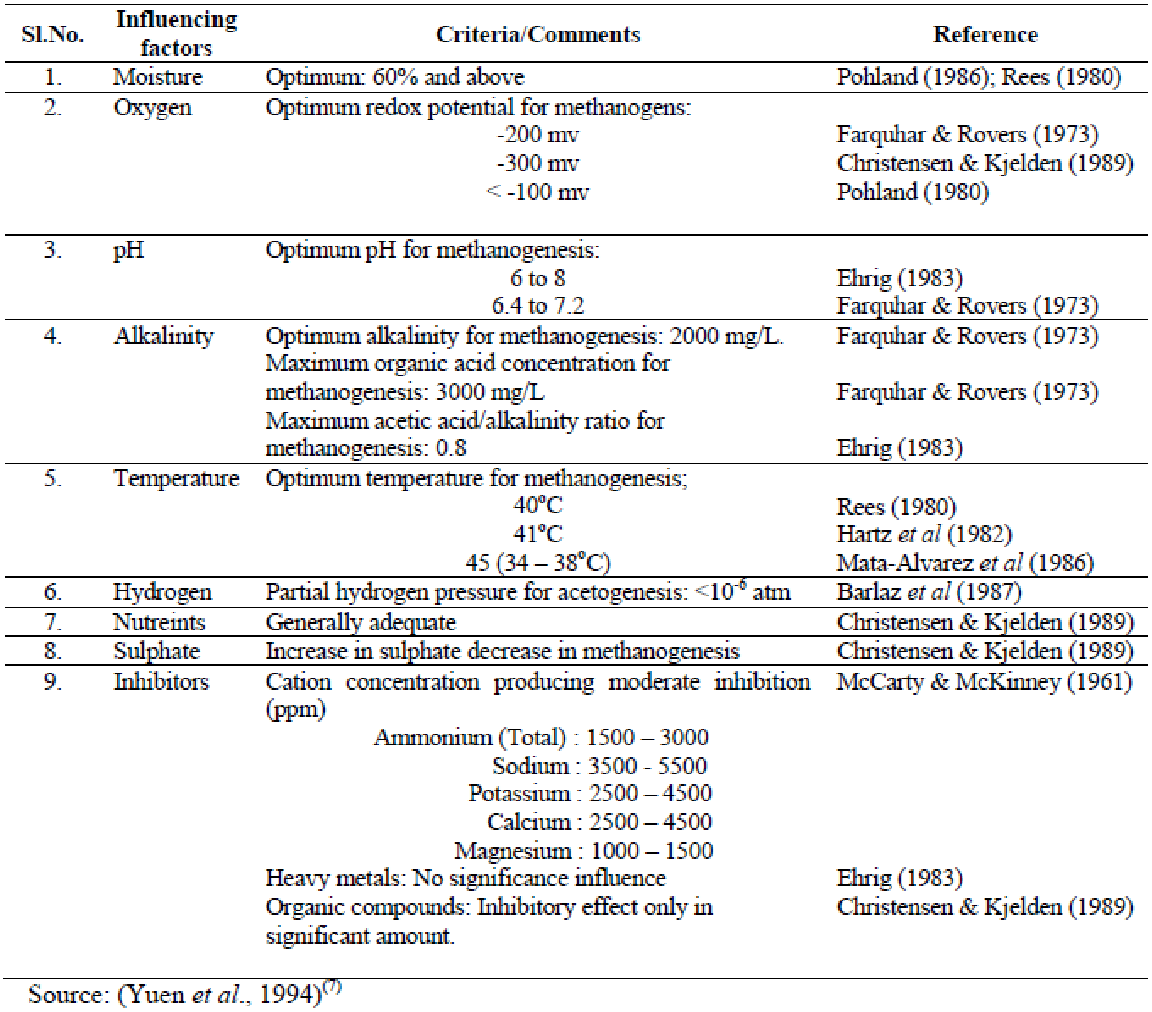
According to Hartz et al., (1982) the optimum temperature for methanogenesis was 41°C; whereas Mata-Alvarez et al., (1986) presented a range of 34 to 38 C.

v) Nutrients

According to Christensen and Kjeldsen (1989), the availability of nutrients for decomposition in the landfill waste is adequate. The degradation process slows down due to the depreciation of nutrients.

A summary of influencing factors of MSW degradation in landfills is shown in Table 2.14 (Karthikeyan & Kurian, 2006).

Table 2.14 Summary of influencing factors on msw degradation in landfills



Sl.No.	Influencing factors	Criteria/Comments	Reference
1.	Moisture	Optimum: 60% and above	Pohland (1986); Rees (1980)
2.	Oxygen	Optimum redox potential for methanogens:	
		-200 mv	Farquhar & Rovers (1973)
		-300 mv	Christensen & Kjelden (1989)
		< -100 mv	Pohland (1980)
3.	pH	Optimum pH for methanogenesis:	
		6 to 8	Ehrig (1983)
		6.4 to 7.2	Farquhar & Rovers (1973)
4.	Alkalinity	Optimum alkalinity for methanogenesis: 2000 mg/L.	Farquhar & Rovers (1973)
		Maximum organic acid concentration for methanogenesis: 3000 mg/L	Farquhar & Rovers (1973)
		Maximum acetic acid/alkalinity ratio for methanogenesis: 0.8	Ehrig (1983)
5.	Temperature	Optimum temperature for methanogenesis;	
		40°C	Rees (1980)
		41°C	Hartz *et al* (1982)
		45 (34 – 38°C)	Mata-Alvarez *et al* (1986)
6.	Hydrogen	Partial hydrogen pressure for acetogenesis: $<10^{-6}$ atm	Barlaz *et al* (1987)
7.	Nutreints	Generally adequate	Christensen & Kjelden (1989)
8.	Sulphate	Increase in sulphate decrease in methanogenesis	Christensen & Kjelden (1989)
9.	Inhibitors	Cation concentration producing moderate inhibition (ppm)	McCarty & McKinney (1961)
		Ammonium (Total) : 1500 – 3000	
		Sodium : 3500 - 5500	
		Potassium : 2500 – 4500	
		Calcium : 2500 – 4500	
		Magnesium : 1000 – 1500	
		Heavy metals: No significance influence	Ehrig (1983)
		Organic compounds: Inhibitory effect only in significant amount.	Christensen & Kjelden (1989)

Source: (Yuen *et al*., 1994)(7)

Landfill Stabilization

Landfill waste stabilization is directly related to the amount of methane generation. The methane generated from organic waste in a landfill is an indicator of waste stabilization. Low methane generation means higher waste stabilization, which indicates a diminution of organic content. Townsend et al., (1996) stated that the rate of landfill stabilization depends on various environmental conditions, in which moisture content is predominant. Moisture content increases due to leachate recirculation and simultaneously enhances waste decomposition that accelerates landfill stabilization.

Leckie et al., (1979) reported two criteria to be considered in a stabilized landfill: 1) settlement reaches its maximum value, 2) leachate is not a pollution hazard. It is necessary to determine the rate and time of landfill stabilization for operation and management. The ratio of organic carbon to the total carbon estimates the degree of biological stabilization of the landfill (Carnes, 1977). A low ratio indicates that most of the stabilization has occurred. Volatile organic content (VOC) is another technique used to measure landfill stabilization.

Several researchers have monitored leachate characteristics, gas production and composition, and chemical composition of the MSW to assess landfill stabilization (Barlaz 1989) and landfill lysimeters (Pohland 1975, 1979; Kinman et al., 1987). The reported advantages of landfill stabilization are a) minimization of environmental contamination, b) reduction in post closure costs, and c) increased potential for landfill reclamation. Qian et al., (2002) stated that the post-closure uses of MSW landfills means the usage of landfill after stabilization. Potential uses are golf courses/driving ranges, sport fields, paths and nature walks, wildlife and conservation areas, parking lots, equipment/material storage, and light industrial buildings.

Mining is one of the major utilizations of a stabilized landfill. Landfill mining is a modern concept that has several benefits for landfill operation, including a) reuse of the same landfill, b) minimizes the need for new land, c) non-degradable materials can be processed to gain more revenue.

CHAPTER 3

FREQUENCY OF LEACHATE RECIRCULATION FOR SUCCESSFUL BIOREACTOR LANDFILL OPERATION

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ABSTRACT

Bioreactor landfill operations, with the addition of leachate, accelerate waste decomposition, gas generation, and waste stabilization. The application frequency of leachate recirculation is one of the major concerns for an effective bioreactor operation; however, a very limited number of systematic field studies have been conducted so far on the application frequency of leachate recirculation for efficient bioreactor landfill operation and the frequency number is not well established yet. Therefore, the objective of the current study was to determine the optimal frequency of leachate addition to a bioreactor landfill. The study was conducted in the City of Denton’s municipal solid waste landfill from May 2009 to June 2016. Electrical Resistivity Imaging (ERI) tests were performed along three zones to obtain baseline resistivity profiles. ERI tests were conducted at intervals of one day, one week, and two weeks after the leachate recirculation. Moisture contents were also estimated around the leachate recirculation pipes from the field ERI results. The estimated results indicated that the initial moisture content for the baseline was ranges from 26.2-31.5% before any leachate/recirculation adjacent to the recirculation pipe. The observed moisture contents after 1 day, 1 week (7 days), and two weeks (14 days) after leachate recirculation were ranges from 47.9-64.5%, 40.4-46.8%, and 30.5-35.7%, respectively. Based on the results, it was summarized that the moisture content decreased with time after recirculation and rebounded almost to its pre-existing state approximately two weeks (14 days) after leachate recirculation. Therefore, it can be concluded that optimum frequency for leachate recirculation for effective bioreactor operation is two weeks (14 days).

INTRODUCTION

Modern landfills are well-structured systems that dispose of municipal solid waste (MSW) to protect the environment from contaminants and to maintain federal regulations. MSW landfills generally accept non-hazardous solid waste, including household waste, non-hazardous sludge, industrial solid waste, and construction and demolition debris. According to the United States Environmental Protection Agency (EPA, 2015), 254 tons of solid waste were generated in the US in 2013, with 167 million of those tons (65.7%) discarded into the landfills. The design and operation of most MSW landfills in the US follow the principle of Subtitle D of the Resource Conservation and Recovery Act (Federal Register, 1991) to minimize the amount of moisture intrusion and retention into the solid waste mass. This design system minimizes groundwater and atmosphere pollution by controlling the generated leachate and gas, and is known as a conventional landfill (Benson et al., 2007). In conventional landfills, the decomposition rate of waste is slow because moisture intrusion and retention in the waste is minimal. As a result, it takes a long time to completely decompose the landfill waste. The most common method used to enhance waste decomposition is the addition of moisture or leachate recirculation, as proposed by Pohland in the 1970s (Pohland, 1975). These are known as bioreactor landfills or enhanced leachate recirculation (ELR) landfills.

A bioreactor landfill is an alternative approach to the conventional landfill, where leachate is recycled into the system. There were two main operating conditions discussed in the first EPA Workshop (1981): the moisture content and the pH. The workshop concluded that the moisture content must be maintained at field capacity, and the pH must be kept near the neutral level. Bioreactor or ELR landfills introduced the concept of adding water to the landfilled waste to increase microbial activities, which enhances waste decomposition. The effects of leachate recirculation on landfilled waste degradation have been conducted by numerous researchers. According to the study of Reinhert & Yousfi (1996), leachate recirculation has significant impacts on leachate composition, gas production, leachate stabilization rate, and waste volume reduction. The added moisture provides better interactions among insoluble substrates, soluble nutrients, and microorganisms to accelerate microbial activities (Barlaz et al., 1990). The enhanced waste decomposition, due to the additional moisture, makes a bioreactor landfill a favorable choice for landfilling. Several researchers have described the advantages of bioreactor landfills (Barlaz et al., 1990; Reinhart and Townsend, 1997; Pohland and Kim, 1999). The rate of settlement is intensified due to enhanced decomposition (Edil et al., 1990; El-Fadel et al., 1999; Hossain et al., 2003), which provides additional air space before closure and minimizes the potential for settlement-induced damage of the final cover (Benson, 2000). The rate of gas production is also increased, due to the enhanced waste decomposition, by improving the viability of gas-to-energy options (Klink and Ham, 1982; Findikakis et al., 1988; Barlaz et al., 1990; Mehta et al., 2002). In addition, a bioreactor landfill can also reduce leachate treatment costs (Pohland, 1975 &1980; Reinhart et al., 2002).

Leachate recirculation, which is one of the major considerations for operation and practice of a bioreactor landfill, is currently allowed for municipal solid waste landfills. The concept is to collect the leachate from the base of the landfill and then reinject it into the waste mass by one of several methods, such as horizontal recirculation pipe, vertical recirculation well, or permeable blanket. There are various important aspects of leachate recirculation that are of interest to regulators, but the prime one is to achieve sustainability. The goals of sustainability are as follows: i) manage the outputs completely (liquids and gas), ii) provide acceptable residues for the environment, iii) eliminate care periods for long-term post-closure, and iv) utilize the closed site for potentially beneficial purposes (Qian et al., 2002).The ultimate goal of leachate recirculation is to enhance the waste degradation, turning the landfill into a massive anaerobic reactor.

The distribution of moisture and the extent of leachate recirculation are the primary concerns when attempting to optimize the performance of a bioreactor landfill. A leachate recirculation system installed in the bioreactor landfill is subjected to spreading the moisture uniformly throughout the landfill. However, due to very high heterogeneity of municipal solid waste (MSW) and the different compaction levels in landfill, the moisture distribution may not be uniform throughout the entire landfill. Therefore, monitoring moisture movement and the direction of the flow after leachate recirculation is an important step in ensuring the efficiency of a recirculation system. In addition, for economic and environmental safety purposes, the addition of leachate needs to be studied over time. Waste stabilization can be maximized by carefully selecting leachate recirculation frequency. The high volume of leachate recirculation may cause various problems such as saturation, ponding, and acidic conditions (Chan et al., 2002). As a result, leachate recirculation should be properly adjusted in order to maintain minimal quantity. Waste decomposition can be enhanced by an increase of moisture (Chugh et al., 1998, Christensen, 2012). Therefore, the application frequency of leachate recirculation is one of the prime concerns of operating a bioreactor landfill effectively.

Electrical Resistivity Imaging has been adopted, at several locations around the world, as the best method to monitor leachate recirculation. This technique has been successfully used in the past by researchers to determine the moisture movement during leachate recirculation in the landfill (Gawande et. al., 2003, Grellier et al., 2007, Grellier et al., 2008, and Rosqvist et al., 2007). The objective of the current study was to determine the application frequency of leachate recirculation of a bioreactor/ELR landfill, using the ERI method. The moisture distributions were monitored by utilizing the ERI technique.

METHODOLOGY

Research on leachate recirculation of bioreactor/ELR landfills is a prime concern today with the advancement of time, technology, benefits, and requirements. Leachate recirculation increases moisture content inside the landfill, and the distributed moisture enhances waste decomposition over time. Hence, the purpose of the current study is to establish a clear understanding of the moisture distribution inside the MSW landfill with time. In this methodology section, the landfill description, recirculation pipe system, and field investigation program are described to present a clear overview.

Site Description

The current study was conducted at the City of Denton Landfill, Denton, Texas, US, where the conventional landfill operation began in 1984. In May 2009, the landfill was upgraded from a waste storage facility to a waste processing facility, after getting the regulatory permit to operate as a bioreactor/ELR landfill. The total footprint of the landfill is approximately 152 acres that consists 7 different cells (0 to 6), as presented in Figure 3.1. The study was conducted at Cell 2 (2A, 2B, and 2C) where the leachate recirculation system was installed.

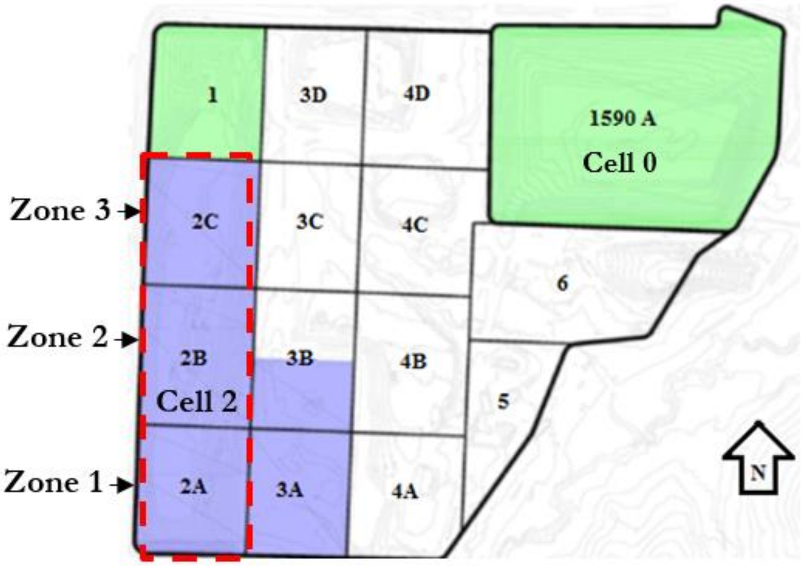


Figure 3.1 Cell configuration of the City of Denton MSW landfill

Field Investigation Program

The main objective of the field investigation was to the determine moisture distribution inside the landfill with time. Electrical resistivity imaging technology was utilized to conduct moisture accumulation, and baseline tests were performed before leachate recirculation into the waste. Moreover, ERI tests were also conducted at intervals of 1 day, 1 week (7 days) and 2 weeks (14 days) after leachate recirculation to investigate the influence of distributed moisture in the zone. To accomplish the research, the total field investigation time was divided into two segments: first three years (May 2009 to April 2012) was the frequency developing period and rest of the years (2013 to 2016) was the evaluation period.

Electrical Resistivity Imaging

Electrical Resistivity Imaging is a non-destructive and very sensitive method which is used to conduct geo-physical properties (i.e., degree of saturation, moisture content, or fluid composition). The method works on the principle of Ohm's law, where the resulting potential differences are measured by transferring artificially-generated currents to the sounding medium. An easier detection of the soil properties depends on the greater electrical contrast between the soil matrix and heterogeneity (Samouëlian et al., 2005). The ERI method is affected by moisture content, temperature, porosity, particle size, pore fluid composition, and clay content (Gueguen and Palciauskas, 1992; McCarter, 1984; Grellier et al., 2007). One of the major properties that can be detected by ERI is moisture content, because, along with other factors, resistivity varies with the presence of water. The electrical current is delivered to the soil or waste material, and the resulting potential difference is conducted. A minimum of four electrodes is required to measure the electrical resistivity, where two electrodes, A and B, are known as current electrodes, and M and N are recognized as potential electrodes, as presented in Figure 3.2. The current electrodes are used to deliver the current in the soil, and the resulting potential difference is determined by the potential electrodes.

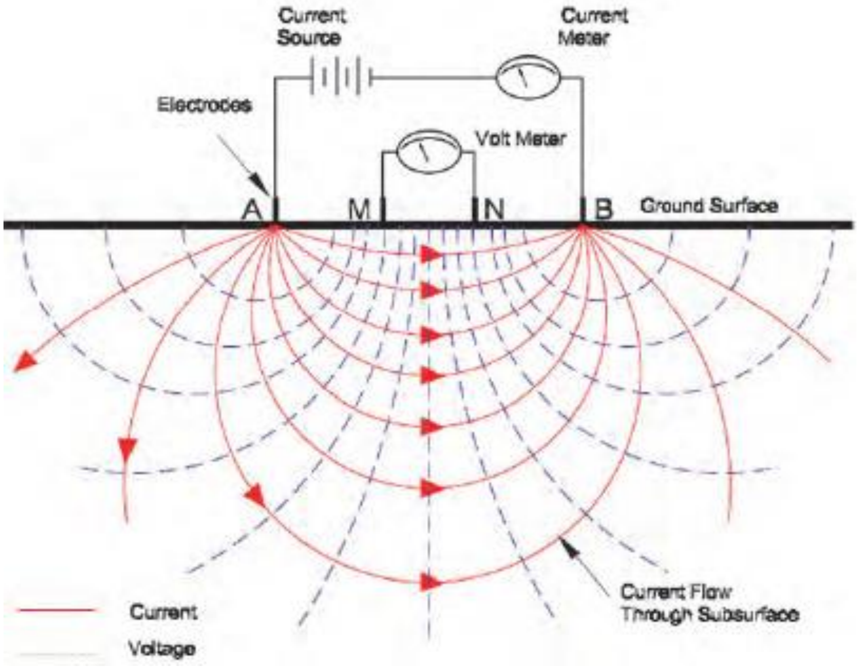


Figure 3.2 Equipotential and current Lines for a pair of current electrodes A and B (Muchingami et al., 2013)

The purpose of electrical resistivity imaging is to depict an overall picture of subsurface resistivity distribution. A two-dimensional multi-electrode system provides a vertical image of the sounding medium. In 2D resistivity imaging, current and potential electrodes are utilized to perform the survey where a fixed distance between two electrodes is always maintained.

Selection of Recirculation Pipes

Horizontal recirculation pipes were mainly utilized to recirculate water/leachate into the waste at Cell 2. In order to investigate the frequency of leachate recirculation of a bioreactor/ELR landfill, a total of five recirculation pipes, H2, H16, H18, H22 and H26, were selected in this current study. The recirculation pipes were selected mainly based on the maximum amount of leachate recirculation in a single pipe, in a specified zone. For the ease of investigation, the total study area (Cell 2) was divided into three zones. The study zones are presented in the Figure 3.3, where zone 1 (Z1) started from Pipe H1 and ranged up to Pipe H5. Zone 2 (Z2) and zone 3 (Z3) ranged between pipe H11 to pipe H16 and pipe H20 to pipe H29, respectively. In each zone, three resistivity lines were considered across the pipe, where line A-A' was conducted on west side, line B-B' at the middle, and line C-C' was conducted along the temporary road near the east side of Cell 2.

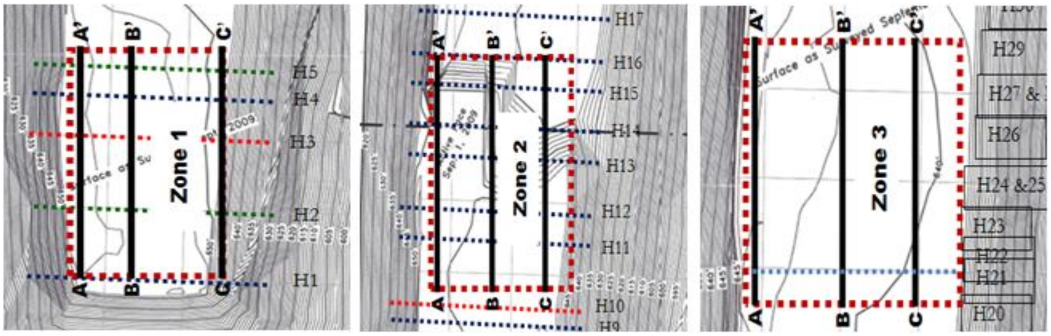


Figure 3.3 RI lines and three different zones at Cell 2

Three years (May 2009 to April 2010, May 2010 to April 2011, and May 2011 to April 2012) of resistivity imaging results were analyzed to determine the frequency of leachate recirculation of bioreactor/ELR landfills. The horizontal recirculation pipes H2 and H16 were selected from zone Z1 and zone Z2 for the three-year of study to observe the moisture variation over time. In addition, pipes H26, H18, and H22 were chosen from zone Z3 to monitor the effects of moisture distribution.

Field Investigation Using ERI Method

The field test process consisted of the electrodes being inserted into the ground and connected to each other through a cable. The multichannel Supersting R8 system measured the subsurface profile with the connection of the switch box and electrode-cable system. In the resistive imaging (RI) method, the electrode spacing depends on several parameters, i.e., required resolution for site investigations, sizes of objects under investigations, and depth of penetration required for the site investigations. A better resolution may be achieved using smaller electrode spacing, where the penetration depth will be smaller. For the same number of electrodes, larger penetration depth would necessitate larger electrode spacing. Therefore, 56 electrodes, spaced 1.83 m (6 ft.) apart were utilized in the current study to conduct the resistivity test, covering the total depth of approx. 20.7 m (68 ft.), which is almost equal to the landfill height. In addition, dipole-dipole array configuration was utilized, which provides the best resolution.

QUANTIFICATION OF MOISTURE CONTENT

The apparent resistivity data was stored in the Supersting R8/IP as raw format after finishing the ERI test. The raw data was downloaded from the Supersting R8/IP meter and analyzed using AGI Earth Imager 2D software (AGIUSA Inc., 2004). The measured resistivity imaging results were further analyzed to determine moisture content. An equation developed by Shihada (2011) was utilized to predict moisture content. The equation is presented as below.

$$x_1 = \frac{3.35056 - \log y - 0.01936x_2 - 0.018156x_3}{0.0240825 - 0.00023668x_3}$$

Where:

X_1 = Moisture content in percentage (wet basis); Y = Electrical resistivity in ohm-m; X_2 = Unit weight (lb./ft^3) of MSW; X_3 = Paper composition in percentage.

The value of Y is chosen from the direct field electrical resistivity imaging test, whereas $X_2$and X_3 are taken from the field compaction and characteristics of MSW.

FACTORS AFFECTING IN QUANTIFICATION OF MOISTURE CONTENT

The major affecting parameters for quantifying moisture content using the developed equation are electrical resistivity imaging, unit weight of MSW, and percentage of paper in the MSW. In addition, hydraulic conductivity and the amount of leachate recirculated also play major roles in moisture distribution. The decomposition of MSW directly depends on the unit weight of the MSW, the percentage of paper, hydraulic conductivity, and recirculation amount. Ten bags of MSW samples were collected every six months from the City of Denton Landfill, and parameters were determined. The same amount of leachate recirculation was also collected, and the values of the affecting parameters are presented in Table 3.1.

Table 3.1 Obtained and reported optimum values of affecting factors

Factors	**Obtained**		**Reported Optimum**		**Average**
	Minimum	Maximum	Minimum	Maximum	
Electrical Resistivity Imaging (Ohm-m)	1	100	–	–	–
Unit Weight of MSW (kg/m3)	319.5	733.8	480	520	–
Paper Composition (%)	16.8	54.3	–		33
Hydraulic Conductivity (cm/sec)	9.87E-06	1.29E-02	9.00E-04	1.10E-03	–
Recirculation Amount (m^3/month/pipe)	18.93	151.42	–		–

RESULTS AND DISCUSSION

These results summarize the present moisture distribution in the City of Denton Landfill, obtained by using ERI. The purpose of the site investigations was to study the possible flow path and areas of moisture accumulation after leachate recirculation in the landfill.

Determination of Moisture Content at Cell 2

Recirculation pipes H2, H16, H18, H22, and H26 were selected, for all three years of the study, to conduct moisture around the pipes. An ERI test was performed across the each pipe before leachate recirculation as a baseline study. To observe moisture distribution over time, ERI tests were also conducted at intervals of 1 day, 1 week (7 days), and two weeks (14 days) after leachate recirculation. For simplicity, the resistivity imaging results of pipe H2 only are presented in Figure 3.4, as the other pipes showed a similar trend. This may have occurred because of identical composition, uniform compaction, and a similar amount of leachate recirculation.

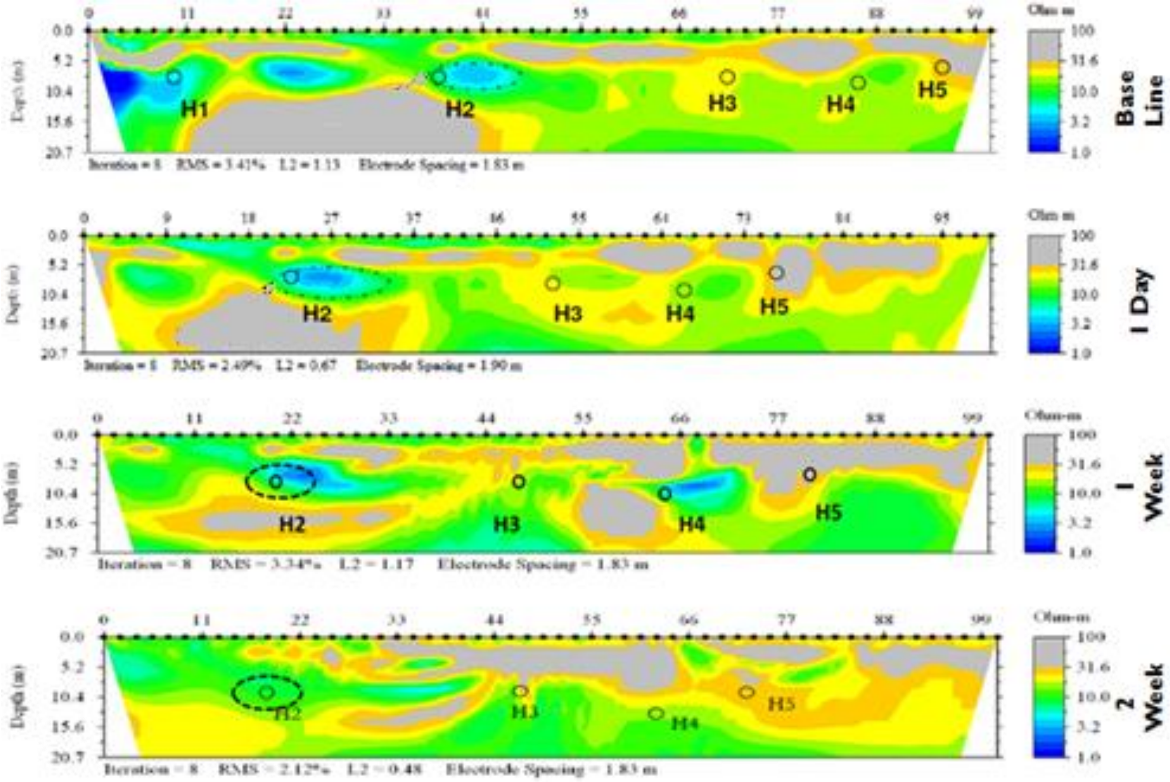


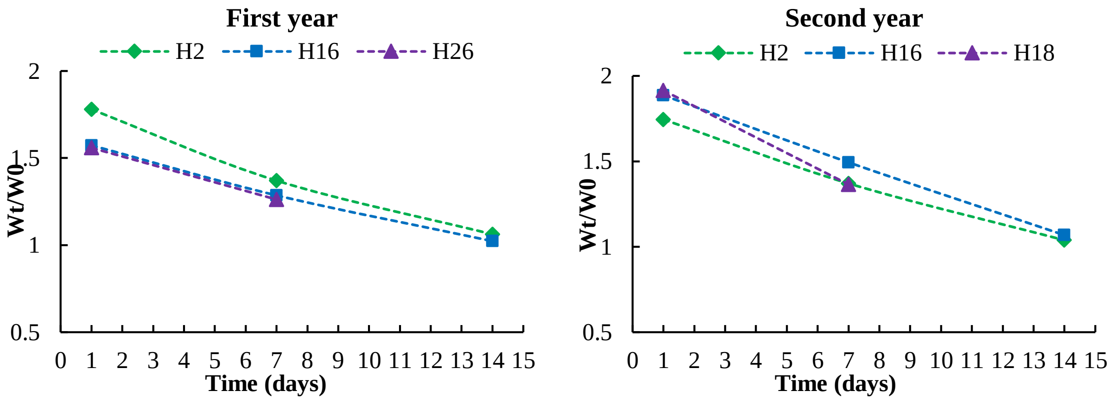
Figure 3.4 Resistivity imaging results of pipe H2

A significantly high resistivity gray zone was observed near the pipe H2 in the baseline study. The ERI results, after 1 day of leachate recirculation, indicated the presence of low resistivity, blue zone, and a decrease of the high resistivity area. The low resistivity zone expanded, and the high resistivity area decreased after 7 days of leachate recirculation. The ERI results 14 days after leachate recirculation showed mostly green and yellow areas, which indicated moderate resistivity value. The resistivity results of pipe H2 for first year are presented in Figure 3.4 and indicate that the resistivity value for the baseline study was 18.1 ohm-m. The observed RI results are 6.6, 11.2, and 17.9 ohm-m after 1 day, 1 week, and 2 weeks of leachate recirculation, respectively. The variation from baseline to 2 weeks (14 days) was due to moisture movement (horizontal and vertical), leachate generation, and waste decomposition with time.

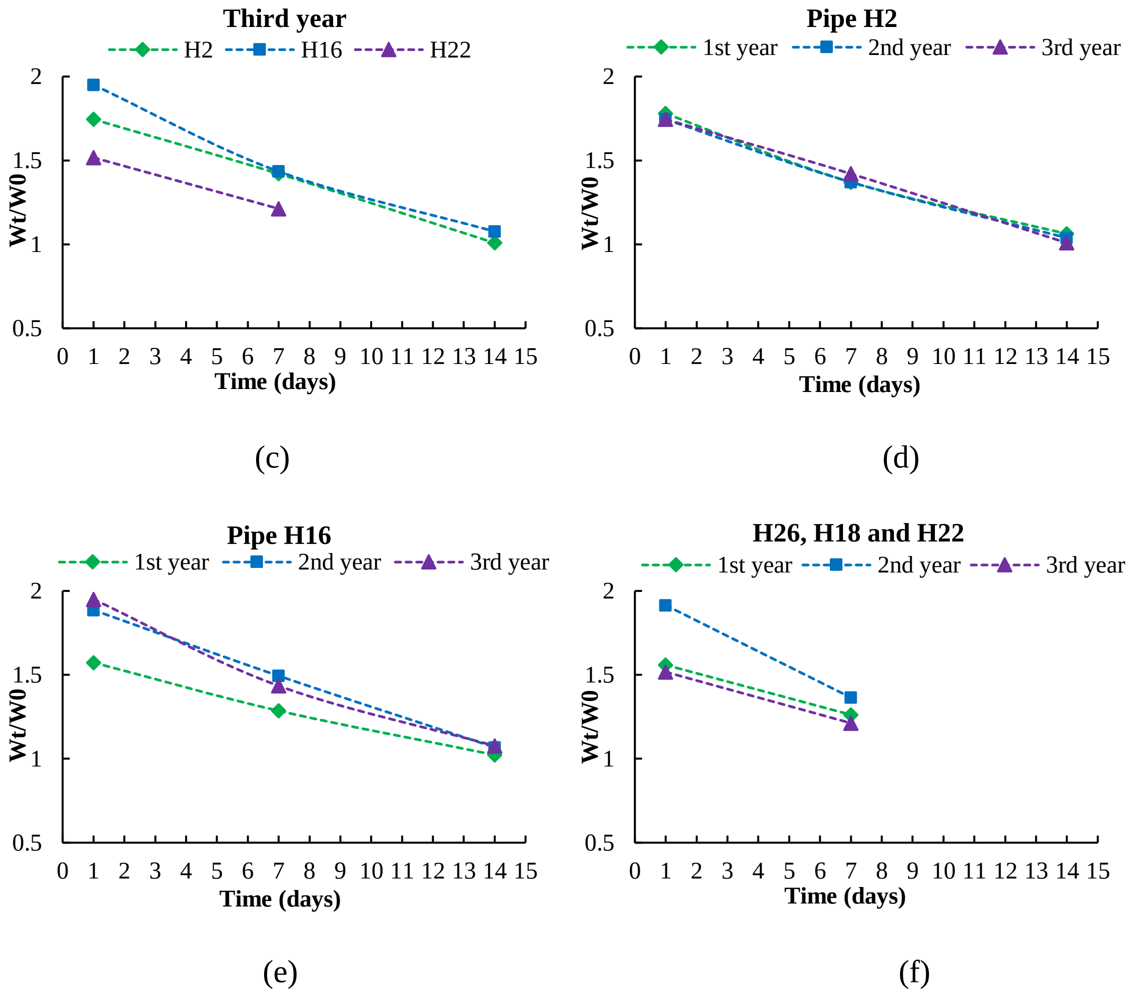
The baseline result indicated that the determined moisture content around pipe H2 was approximately 31.48%. The estimated moisture content after 1 day, 1 week, and 2 weeks of leachate recirculation was 49.52, 40.48, and 31.74%, respectively. Similar ERI results were obtained for the year May 2010 to April 2011 (second year) and May 2011 to April 2012 (third year). In the second and third years, RI results of pipe H2 were considered since the other pipes showed similar results. The moisture content of the baseline study after 1 day, 1 week, and 2 weeks after leachate recirculation for the second year was estimated at 31.48, 59.38, 47.03, and 32.68%, respectively. Likewise, in the third year, moisture contents of 31.48, 61.39, 45.16, and 32.95 %were observed for the baseline, 1 day, 1 week, and 2 weeks, respectively, after leachate recirculation.

Frequency Estimation of Leachate Recirculation

The measured data for the first three years' moisture content was further evaluated to determine the frequency of leachate recirculation. The moisture content of the five pipes selected was plotted and indicated a decreasing trend with time, as shown in Figures 3.5 (a, b, and c). In addition, the moisture content of a single pipe for 3 years was plotted, and it also depicted a decreasing trend with time, as presented in Figures 3.5 (d, e, and f). A baseline was plotted, based on the baseline study for each case. Moisture content increased significantly after one day of leachate recirculation, with the observed moisture content ratio ranging from 1.5 to 2.0. The RI values decreased with time after 1 week (7 days) of leachate recirculation compared to 1 day of RI values, due to distribution and usage effects, and the determined moisture content ratio ranged from 1.21 to 1.50. Finally, the moisture content ratio was observed close to 1.0 after 2 weeks (14 days) of leachate recirculation because distribution and usage were almost complete. The results showed that the moisture content rebounds back almost to its pre-existing state after 2 weeks (14 days) of leachate recirculation. The distribution and usage of added leachate or water takes time due to the compaction, heterogeneity of waste, and slow degradation process effects. Therefore, the results indicated that the presence of moisture was minimum inside the landfill after 2 weeks (14 days) of leachate recirculation which confirms the necessity of leachate for further enhanced waste decomposition.



(a) (b)



(c) (d) (e) (f)

W_0 = Moisture Content with Respect to Baseline, W_t = Moisture Content with Time

Figure 3.5 Moisture content ratio with respect to time

Developing a Recirculation Prediction Model

From the evaluation period results, the goal was to develop a generalized field frequency curve. ERI tests were performed randomly after leachate recirculation in the evaluation period to observe moisture distribution with time. Based on the moisture content ratio obtained from five pipes corresponding to three different zones, statistical analysis was undertaken to develop a recirculation model. Data from three different zones considered all pipes plotted together in order to develop a model. A scatter plot of the data is shown in Figure 3.6. The selected data was analyzed in a statistical environment. Based on the analysis, a simple liner model best fitted the data. The details of the model are provided in Table 3.2.

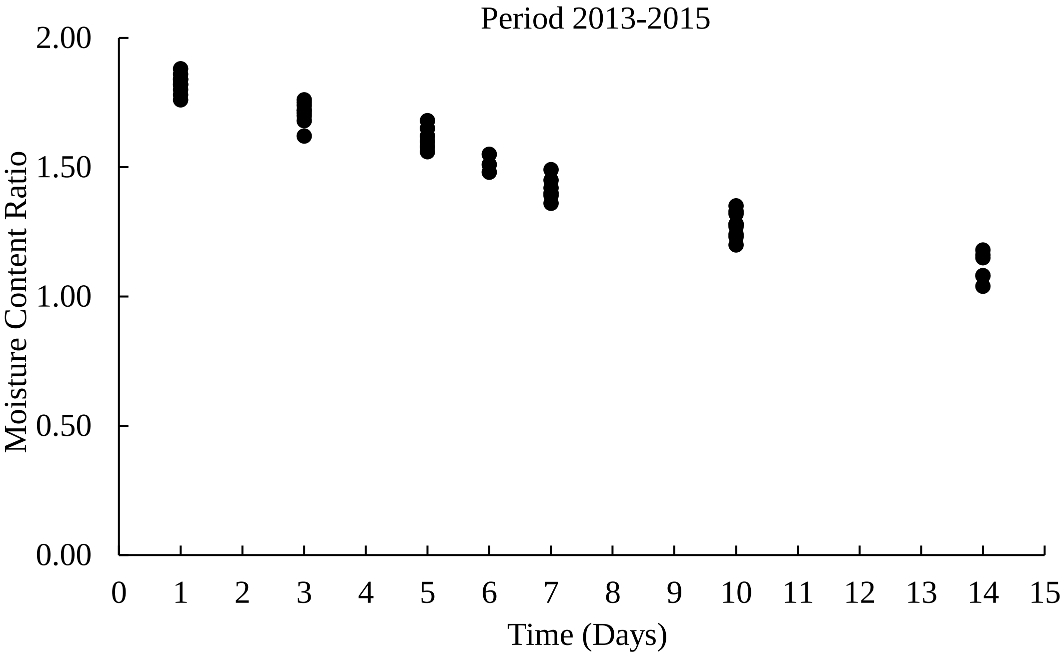


Figure 3.6 Scatter plot of all moisture ratio data

Table 3.2 Properties of initial linear prediction model

SSE	R^2	R^2 (Adj.)	RMSE
0.2976	0.8589	0.8524	0.1163

Y = (-0.0544 * X) + 1.775; where, X = time (days) and Y = moisture ratio with respect to the baseline. According to the model, the R^2 value is 0.8589, which implies that almost 86% variability of the data can be explained through the developed model. In order to improve the accuracy of the model, the average value for each day was taken into consideration. Based on the average values of corresponding days, different models were tried to fit the values, i.e., exponential, power, polynomial, etc. Eventually, the first degree polynomial (linear) model was found to be simplest and most effective from a statistical viewpoint. A Summary of the recirculation/prediction model is given in Table 3.3.

Table 3.3 Properties of final linear prediction model

SSE	R^2	R^2 (Adj.)	RMSE
0.002414	0.9602	0.9504	0.04913

$Y = (-0.05372 * X) + 1.773$; where, X = time (days) and Y = moisture ratio with respect to the baseline. According to the final prediction model, the R^2 value jumped to 0.9602 from the previous one of 0.8589, which clearly indicated the improvement of the model.

Justification of Usage of Average Value

As described in the previous section, average values from each day were utilized to develop the recirculation model because most of the values were clustered in a narrow band. To justify the usage of average values, from a statistical point of view, the Analysis of Variance (ANOVA) approach was used in the statistical software environment. The analysis was conducted at a 95% confidence level indication that $\alpha = 0.05$. The result of the analysis of the One-way ANOVA is presented in Table 3. 4.

Table 3.4 Analysis results of one-way ANOVA

Analysis of Variance	
F-Value	P-Value
69.27	0

As can be seen, the p-value was found to be 0.000, which is less than the α value. The F-value was also pretty high (69.27). Based on the p-value and F-value, a null hypothesis, that means are equal, can be rejected, which indicates that there is significant difference between the three means for the three days. Taking this into consideration, as well as the 95% confidence level, it can be seen that all three average values are within the 95% confidence interval of the three corresponding days, which is presented in following Table 3.5.

Table 3.5 95% Confidence interval and average values

Day	95% Confidence	Average Value
1	(1.6612, 1.8206)	1.740924
7	(1.2776, 1.4370)	1.357287
14	(0.9419, 1.1371)	1.039476

Verification of the Predicted Model

In order to verify the developed model, moisture ratios were calculated from further field monitoring for the period 2016. Data used to verify the model is presented in Table 3.6. Field data and predicted data are plotted in Figure 3.7. As can be seen, for most of the cases observed, data was within 10% of the predicted data, except for that for 24 days. The discrepancy can be due to the fact that the model was developed using data up to 14 days.

Hence, its accuracy is more within the 14-day time limit. Moreover, the observed and predicted values were plotted with a 45 degree inclined straight line shown in Figure 3.8. The plotted trend followed a straight line pattern, indicating good agreement between observed and predicted values.

Table 3.6 Observed and predicted moisture content ratio

Day	Observed moisture ratio in field	Predicted value using equation
1	1.47	1.72
4	1.69	1.56
9	1.24	1.29
9	1.167	1.29
24	0.787	0.48

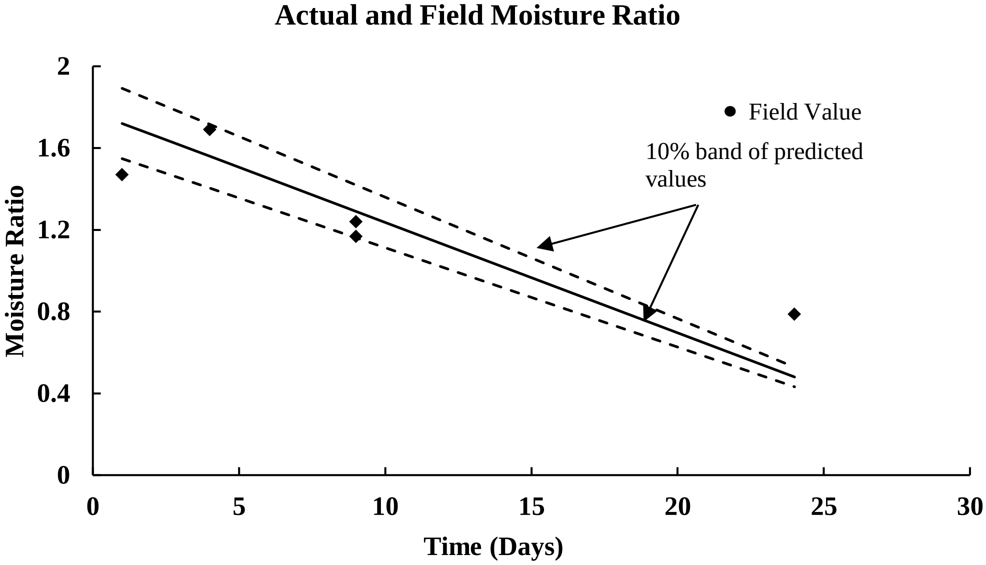


Figure 3.7 Actual and field moisture ratio comparison

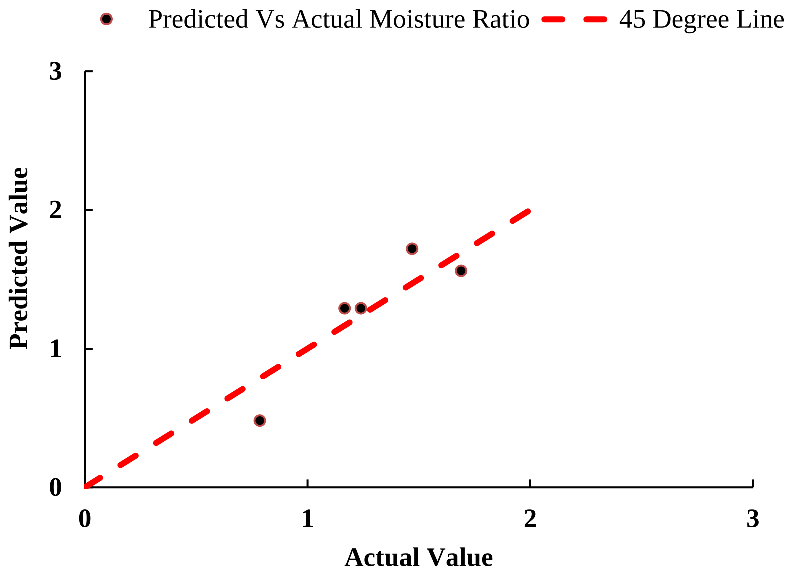


Figure 3.8 Observed and predicted values plotted with 45 degree straight line

Finally, hypothesis testing was performed to verify the model. Two independent sample t-tests with unequal variance were performed to determine whether there were significant differences between the actual and predicted values. The rationale behind the independent test was non-dependency of the two set values. The reason behind the lower sample size can be attributed to heavy labor work associated with the resistivity. In the t-tests, the mean of predicted values was compared against the mean of observed values. The risk level was assumed to be 0.05. The two-tailed test directed the significance level to 0.025 from 0.05. The basic hypothesis can be described as H_0: m_1-m_2=0 and H_a: m_1-m_2≠0; where, m_1-= Mean of the actual moisture ratio and m_2 = Mean of the predicted moisture ratio.

The test summary is provided in Table 3.7. The t-value found from the analysis was lower than that of the critical value of the two-tailed t-test. The P-value was found higher than the significance level (α/2). Based on the analysis, it can be concluded that null hypothesis cannot be rejected, indicating there is no significant difference of means between the actual and predicted ones. Hence, the developed prediction model is justified. Finally, a generalized field frequency curve was developed based on the above model as presented in Figure 3.9. The significance of this field frequency curve was to measure moisture content at the field without doing field investigations.

Table 3.7 Two-tailed test

Two-Tailed Test Results			
T-Test of Difference	T-Value	P-Value	DF
0	0.01	0.992	7

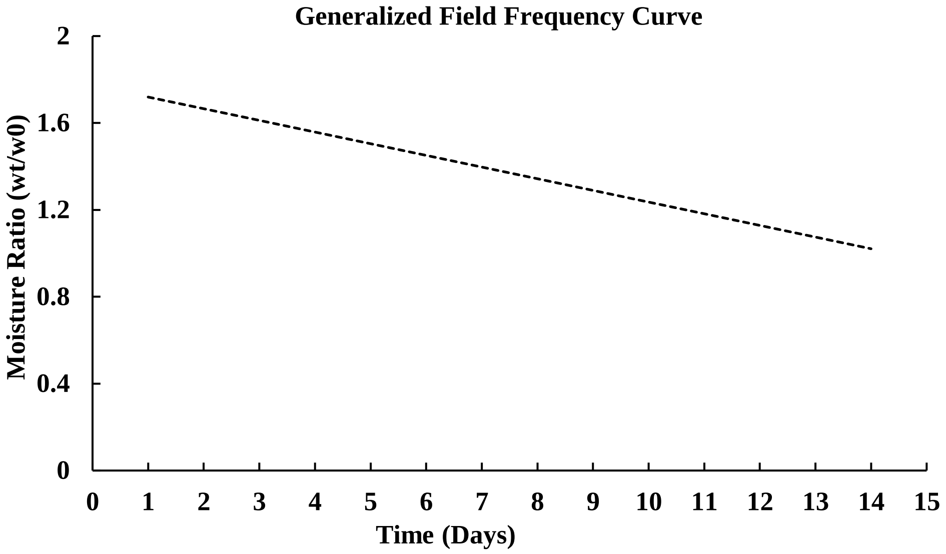


Figure 3.9 Generalized field frequency curve

Validation of the Field Frequency Curve

Benson et al., 2007 conducted a study of five bioreactor/recirculation landfills. The study stated that the application frequency or dose of leachate depends on the availability of the leachate, operational philosophy, regulatory prohibition, weather condition, and the level of magnitude over time. The application frequency or dose was 10-14 days for most of the landfill which was based on mainly operational practice, no field investigation was conducted. However, an extensive direct field measurement was utilized in the current study to determine the frequency of leachate recirculation. The estimated application frequency was 14 days for effective bioreactor operation. The comparisons of the two studies are presented in Tale 3.8.

Table 3.8 Comparison of application frequency of leachate

Study	**Landfill Name**	**Application Frequency**
Benson et. al., (2007)	S	≈ 10-14 days
	D	Varies
	Q	≈ 10 days
	C	≈ 10-14 days
	E	Varies
Current Study	The City of Denton Landfill	≈14 days

CONCLUSIONS

A bioreactor landfill has advantages over a conventional landfill in terms of leachate recirculation or moisture addition which enhances waste decomposition and gas production. For the effective bioreactor operation, the leachate recirculation or dose should follow a certain interval. In the current study, the electrical resistivity imaging was conducted to determine moisture distribution and extent over time. ERI is an appropriate geophysical technique to measure the moisture content in landfills. The method allows water to be located within a landfill, and moisture movement to be seen through the waste mass and the influence zone of the leachate recirculation system. The ERI test was performed before and after any leachate recirculation to evaluate the time effect on moisture distribution. The performed ERI tests, along the recirculation pipe before and after the leachate recirculation, indicated a decrease in resistivity around the recirculation pipe compared to the baseline study before the addition of water. The reduced resistivity contour around the pipe represents the flow of leachate after leachate recirculation through the pipe. The moisture zone, due to leachate recirculation, increased with the addition of leachate and rebounded to its pre-existing state with the increments of time. The leachate application frequency was determined by using electrical resistivity imaging. The obtained results depict that the optimal frequency of leachate recirculation is almost 14 days for a bioreactor/ELR operation.

CHAPTER 4

PERFORMANCE MONITORING OF VERTICAL INJECTION WELLS IN A BIOREACTOR LANDFILL

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ABSTRACT

The operation of a bioreactor or enhanced leachate recirculated (ELR) landfill includes the addition of supplemental water/leachate through a leachate recirculation system for accelerated waste stabilization, enhanced gas generation, and faster air space recovery. Different types of recirculation systems are currently in operation across the world, i.e., horizontal trenches, vertical wells, infiltration blankets, and direct surface applications. Vertical injection wells are currently receiving more interest due to their applicability after the landfill is capped. Therefore, the primary objective of the current study was to monitor the performance of vertical injection wells in leachate distribution in a bioreactor landfill operation at the City of Denton Landfill, Denton, Texas, US. Electrical resistivity imaging (ERI) tests were conducted before and after the injection of leachate/water to identify the moisture distribution around the vertical wells. The moisture distribution was monitored with time (one day, one week, and two weeks after leachate recirculation) to identify the performance of the vertical injection well. Before the liquid addition around the vertical wells, the moisture content ranged from 26.5% to 30.2% and increased after one day of leachate injection (from 39.1% to 63.2%). However, the moisture content decreased after one week of leachate injections (ranging from 32.5% to 55.6%), and after two weeks of leachate injections, the moisture content returned to its initial state (moisture content ranged from 30.5% to 35.8%). Therefore, based on the preliminary test results, vertical recirculation wells can be effectively implemented for moisture distribution within a bioreactor landfill.

INTRODUCTION

A bioreactor or enhanced leachate recirculation (ELR) landfill is the modern concept of landfill operation that involves accelerated waste decomposition, enhanced gas generation, and rapid waste stabilization. Water and/or leachate is added to the landfill through a recirculation system (Pohland, 1975; Barlaz et al., 1990; Pacey et al., 1999; Reinhart et al., 2002; Mehta et al., 2002; Warith, 2002; Benson et al., 2007; Bareither et al., 2008a). Proper management of leachate recirculation is one of the major issues for the effective operational practice of bioreactor or ELR landfills. In order to maximize waste stabilization, leachate recirculation frequency must be carefully selected. If too much leachate is recirculated, problems such as saturation, ponding, and acidic conditions may occur. Several research studies indicated that waste decomposition can be improved by an increase in the moisture flow, as a result of increased flushing and dilution of the inhibitory products, maintenance of favorable environmental conditions by uniform distribution of moisture, and addition of higher quantities of inoculum and nutrients (Chugh et al., 1998; Leuschner et al., 1989). The advantages of leachate recirculation include a) minimizing the risk of damage to the final cover by settling the waste mass, b) increasing the capacity of landfill, c) minimizing off-site leachate treatment cost, d) enhancing gas production to generate more energy, and e) reducing post-closure monitoring time and cost by accelerating waste decomposition (Barlaz et al., 1990; Reinhart and Townsend, 1998; Pohland and Kim, 1999; Doran, 1999; and Mehta et al., 2002).

Leachate recirculation methods usually include horizontal trenches, vertical wells, infiltration blankets, and direct surface applications (Reinhart and Townsend, 1997). The application methods have changed from direct surface infiltration to horizontal trenches, vertical wells, infiltration blankets and working face applications over time. Haydar and Khire (2005) divided leachate recirculation techniques into two categories: surface and subsurface applications. A surface application can be performed by a) direct application or spray irrigation of leachate on the landfill surface, and b) surface ponding of leachate. Subsurface application consists mainly of: a) horizontal trenches, and b) vertical wells (Qian et al., 2002; Khire and Haydar, 2003). The most commonly used of these methods are the horizontal recirculation pipes and vertical injection wells for recirculating leachate into the solid waste mass.

The vertical recirculation system has been utilized to recirculate leachate into a number of the full-scale bioreactor landfills (Watson, 1987; Kilmer and Tustin, 1999; Smith et al., 2000). Jain et al. (2005) performed an evaluation of a vertical well system for leachate recirculation to provide design inputs applicable to future bioreactor operations. A vertical well cluster model with perforated vertical pipes and high permeable materials (backfill) was used, and leachate was recirculated through 11 injection wells for the study.

A typical vertical well system includes perforated vertical pipes surrounded by highly permeable filter material, usually gravel (Reddy et al., 2012). The main advantage of a vertical well system is its installation, since it can be constructed in active or closed landfills. Uniform and adequate distribution can be achieved without causing problems, such as excessive pore pressures and excessive differential settlements. Vertical wells are very common in the landfills where horizontal trenches installation are not cost effective or possible (Haydar and Khire, 2005). Khire and Mukherjee (2007) conducted a study on leachate recirculation using vertical wells in bioreactor landfills to evaluate design variables, with well diameters ranging from 0.05 m (0.164 ft.) to 0.1 m (0.328 ft.), screen height of 3.0 m (9.843 ft.), and depth of 17.0 m. Jain et al., (2010) conducted a study on the steady state design of vertical wells in bioreactor landfills to present a design chart for estimating input values (dimension of vertical wells). The vertical well dimensions were considered to be between 2.5 cm (0.082 ft.) to 250 cm (8.202 ft.) radiuses, 5 m (16.404 ft.) depth, and with a screen length of 2.5 m (8.202 ft.). The modeling results indicated that the lateral and vertical extents of moisture distribution were as much as 30m (98.425 ft.) for 20,000m^3 (7,06,293 ft^3)of liquid addition.

The electrical resistivity imaging (ERI) technique has been adopted to monitor moisture distribution due to leachate injection through vertical wells. Several researchers successfully utilized the technique in the past to determine the moisture movement or variation after leachate recirculation in the landfill (Alam et al., 2016; Gawande et. al., 2003; Grellier et al., 2007; Grellier et al., 2008; and Rosqvist et al., 2007). The objective of the current study was to monitor the performance of vertical injection wells of a bioreactor/ELR landfill, using the ERI method.

METHODOLOGY

Site description

The study area is located at the City of Denton Landfill, Denton, Texas, which began operating in 1984. The landfill operated as a traditional landfill until it received the permit to operate as a bioreactor or ELR landfill in 2009 from the Texas Commission on Environmental Quality (TCEQ). This landfill receives approximately 635,000 kg/day (700 tons/day) of waste. The City of Denton Landfill has seven cells: Cell 1590A, Cell 1, Cell 2, Cell 3, Cell 4, Cell 5, and Cell 6, as illustrated in Figure 4.1. The oldest cell, 1590A, also known as Cell 0, is operated as a conventional landfill, and the rest of the cells are operated as bioreactor landfills. Leachate recirculation systems (horizontal recirculation pipes and vertical injection wells) were installed to inject water or leachate into the landfill. Currently, leachate recirculation is performed in Cell 2, Cell 3, Cell 4, and Cell 5. The study was mainly conducted in Cell1 and Cell 2 in order to monitor the performance of the vertical injection wells (VW 1, VW 2, and VW 3).

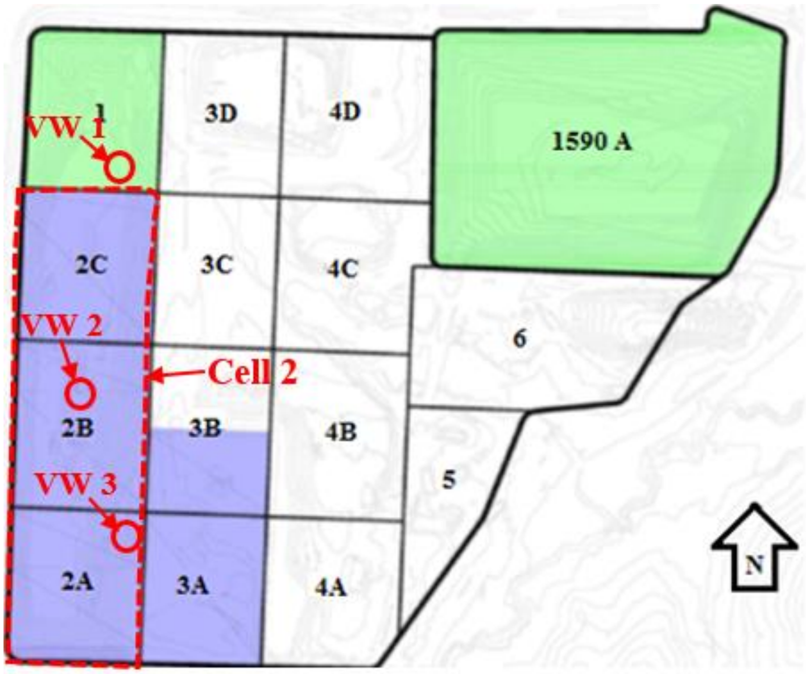


Figure 4.1 Cell configuration of the City of Denton MSW landfill

Selection of vertical injection well

A total of three vertical injection wells, along with 36 horizontal recirculation pipes, are located at the City if Denton Landfill at Cell 1 and Cell 2, to inject water/leachate into the landfill. The vertical wells 1, 2, and 3 are located at Cell 1, Cell 2B, and Cell 2A, respectively. The vertical wells are HDPE pipes with 150 mm (6 in.) diameter, 15 m (50 ft.) screen length, and 21 m (70 ft.) well depth. These pipes are directly connected to the recirculation tank. The pipes were installed using boreholes into the landfill, and were backfilled with high permeable materials around the well. Different amounts of leachate recirculation were conducted through the vertical wells. In the current study, the selected vertical injection was based on maximum injection through a single well to observe moisture variation by using the ERI method. Vertical well 2 was selected according to the selection process, and the layout and ERI lines are presented in Figure 4.2.

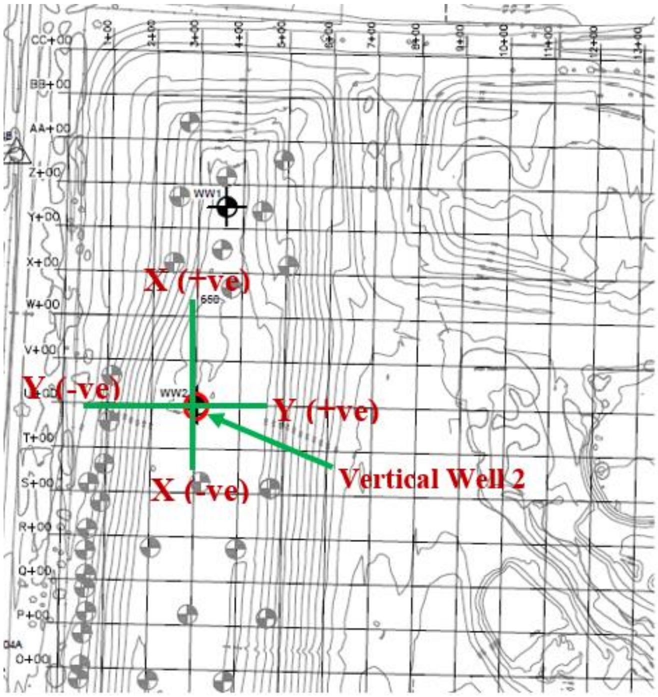


Figure 4.2 Layout of vertical injection well 2 and ERI lines at Cell 2

Field Investigation Using ERI

The ERI test was conducted to determine moisture flow and accumulation within the solid waste due to the leachate recirculation or water addition through vertical injection well 2. ERI is a non-destructive and very sensitive method which is utilized to explore subsurfaces. The method works according to the principle of Ohm’s law, where the artificial current is transferred and the resulting potential differences of the sounding medium are measured. Several parameters affect the ERI method such as moisture content, temperature, porosity, particle size, pore fluid composition, and clay content (Gueguen and Palciauskas, 1992; McCarter, 1984; Grellier et al., 2007). The purpose of ERI is to depict an overall subsurface image of the medium. Investigation of hydrogeological, environmental, and geotechnical parameters have been conducted by using ERI for many years. The electrical resistivity varies with the moisture content, temperature, ion content, particle size, resistivity of the solid phase, permeability, porosity, and clay content present in the materials (Gueguen and Palciauskas, 1992; Shihada, 2011; Kibria, 2014; Abu Hassanein et al., 1996; McCarter, 1984; Michot, 2003; Goyal et al., 1996; Ozcep et al., 2009; and Guerin et al., 2004; Griller et al., 2012).

Two resistivity lines were conducted in a "+" pattern to observe the moisture distribution with time around the well, as illustrated in Figure 4.3. A minimum distance of 15.24 m (50 ft.) in each direction was maintained from the center of the well to perform the test. The assumption was based on the previous study, which reported that the moisture extent from a recirculation pipe was approximately 15.24 m (50 ft.) (Manzur et al., 2016).

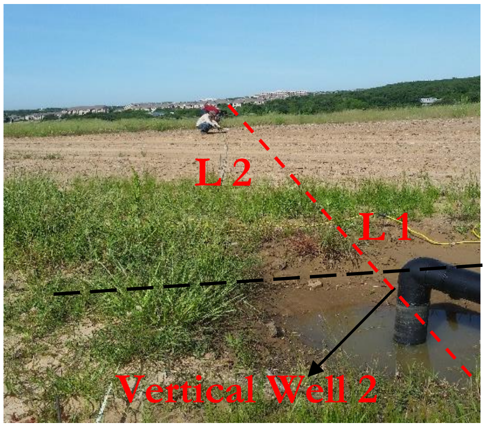


Figure 4.3 Field investigation using ERI

Fifty-six electrodes, with spacing of 1.83 m (6 ft.) were utilized in the current study to conduct the resistivity test to cover the total depth of approx. 20.7 m (68 ft.), which was almost equal to the landfill height. In addition, dipole-dipole array configuration was utilized, which provides the best resolution.

Estimation of Moisture Content from ERI Results

Moisture content was estimated from ERI results by using an equation developed by Shihada (2011). The equation is presented as below.

$$x_1 = \frac{3.35056 - logy - 0.01936x_2 - 0.018156x_3}{0.0240825 - 0.00023668x_3}$$

Where:

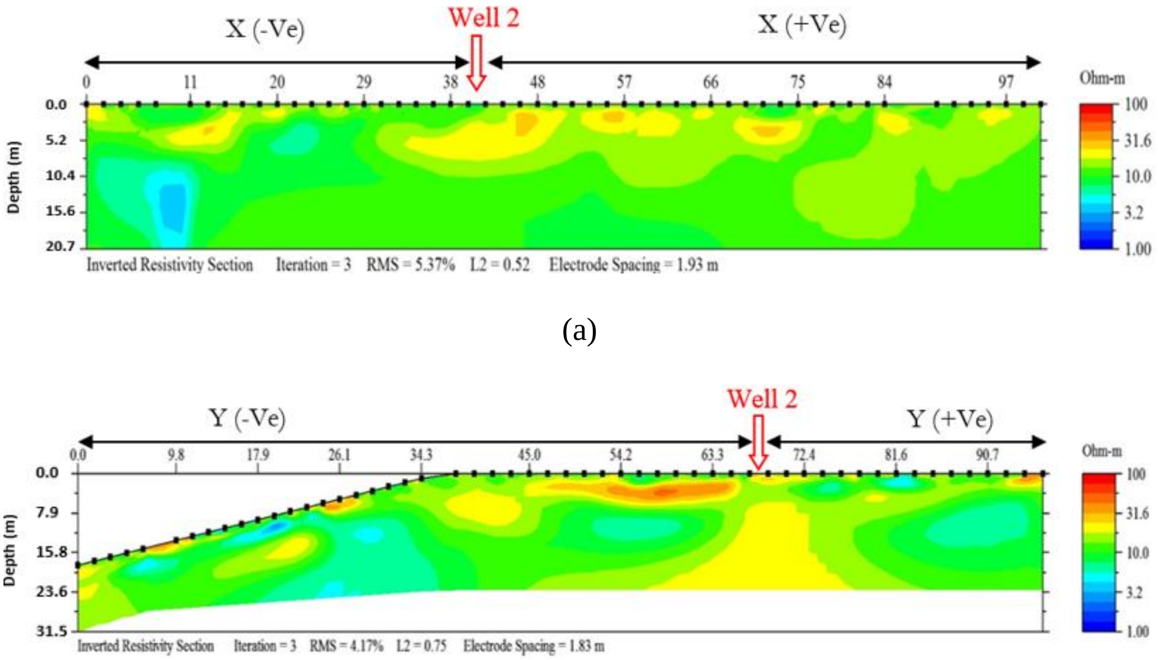
X_1 = Moisture content in percentage (wet basis); Y = Electrical resistivity in ohm-m; X_2 = Unit weight (lb./ft^3) of MSW; X_3 = Paper composition in percentage.

The value of Y is chosen from the direct field electrical resistivity imaging test, whereas X_2 and X_3 are taken from the field compaction and characteristics of MSW.

RESULTS AND DISCUSSION

2D RI Results Analysis

A resistivity profile defines moisture distribution around a vertical injection well. The influence area of moisture around the injection well varies with the quantity of recirculated leachate and distribution time. Before any leachate injection, ERI tests were performed for the vertical well 2, to establish a baseline study. The analyzed baseline results are shown in Figure 4.4. No leachate was recirculated through the vertical well 2 before the baseline studies were conducted, resulting in the influence area indicating a low moisture zone around the well. From the distribution profile, it was observed that the resistivity values were between 23.5 ohm-m and 20.8 ohm-m at 3 m depth for baselines L1 and L2, as presented in Figure 4.4 (a) and Figure 4.4 (b), respectively.



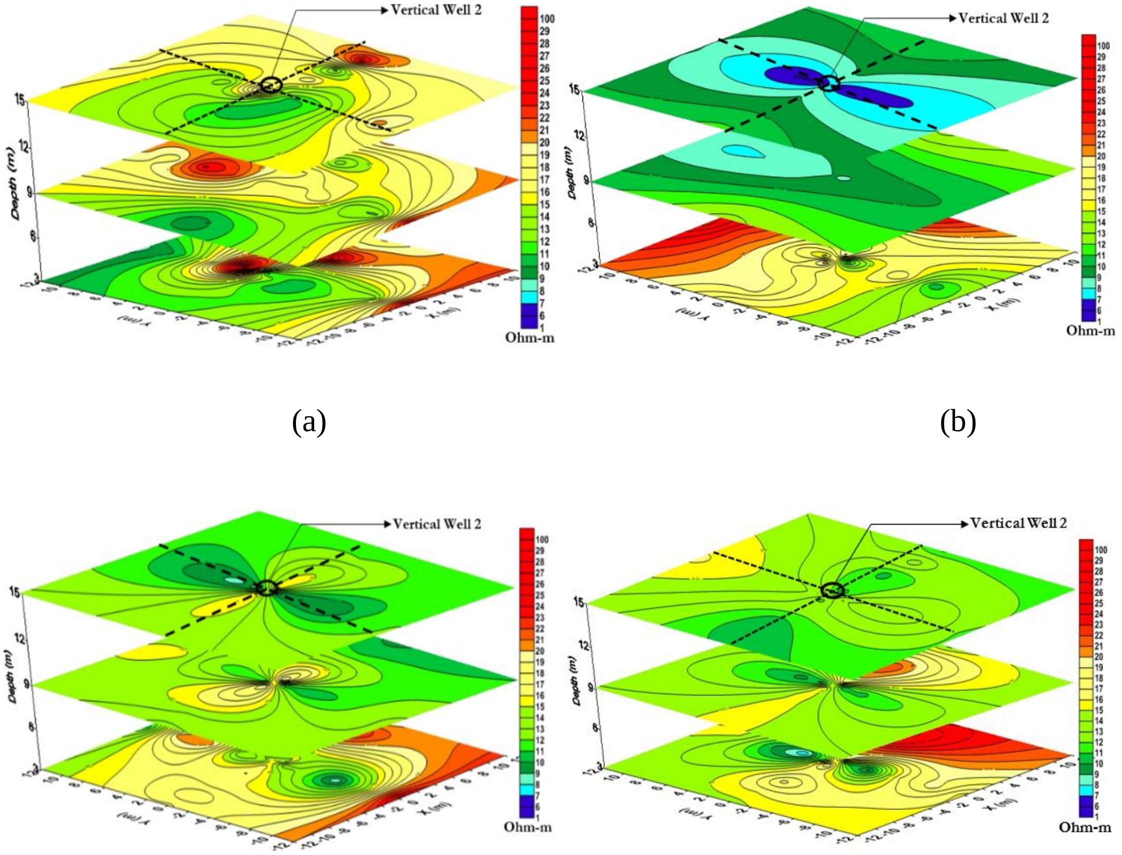
(a)

(b)

Figure 4.4 RI baseline for the vertical well 2: (a) line L1, (b) line L2

3D RI Results Analysis

Further analyses were conducted by 3D plots, using surfer, where line 1 and line 2 were taken as the X-axis and the Y-axis, and the resistivity values were taken as the Z-axis to plot the 3D diagram. The 3D ERI results were further analyzed in three slices, i.e., top, middle, and bottom, as illustrated in Figure 4.5. The slices were taken at 3 m (9.84 ft.), 9 m (29.52 ft.), and 15 m (49.21 ft.) depths to represent the bottom, middle, and top slices from the bottom of the landfill, respectively. The influence of moisture distribution increased with the increment of depth. As a result, the slices were presented from the bottom of the landfill to the top of the landfill, as the upper slice was clearly visible. Figure 4.5 (a) indicates the baseline results, in which most of the area around the pipe has a high RI value, ranging from 12 to 25 ohm-m and denoting low moisture zone.



(a)

(b)

(c)

(d)

Figure 4.5 Moisture distributions at different depths; (a) baseline study, (b) after 1 day, (c) after 1 week (7 days), and (d) after 2 weeks (14 days) of leachate recirculation.

The amount of leachate recirculation was 45,800 liters (12,100 gallons) through the vertical injection well 2 on July 21st, 2015. Figures 4.5 (b, c, and d) depict the RI lines which were performed at intervals of 1 day, 1 week (7 days), and 2 weeks (14 days) after leachate recirculation on July 22nd, July 28th, and August 4th, respectively. After day 1, the results indicated that the resistivity values decreased due to the moisture spreading around the vertical well. A high moisture zone was observed due to the effect of leachate injection through the vertical well, where the resistivity value ranged from 7 ohm-m to 15 ohm-m. A fraction of the recirculated leachate was utilized for waste decomposition, and the rest of the leachate moved laterally and vertically, and then travelled towards the bottom liner. Hence, due to the addition of leachate, the resistivity values, after 7 days, increased. After 14 days, the resistivity values rebounded to the initial resistivity value, similar to the baseline study, after being utilized by the surrounding waste for decomposition.

Analysis for Points A, B, C, and D

The 3D ERI results were further evaluated for the point A [X= 3 m (9.84 ft.); Y= 3 m (9.84 ft.)], B [X = 6 m (19.68 ft.); Y = 6 m (19.68 ft.)], C [X = 9 m (29.52 ft.); Y = 9 m (29.52 ft.)], and D [X = 12 m (39.36 ft.); Y = 12 m (39.36 ft.)] to observe moisture variation around the well with the increment of distance and depth. The schematic diagram is presented in Figure 4.6.

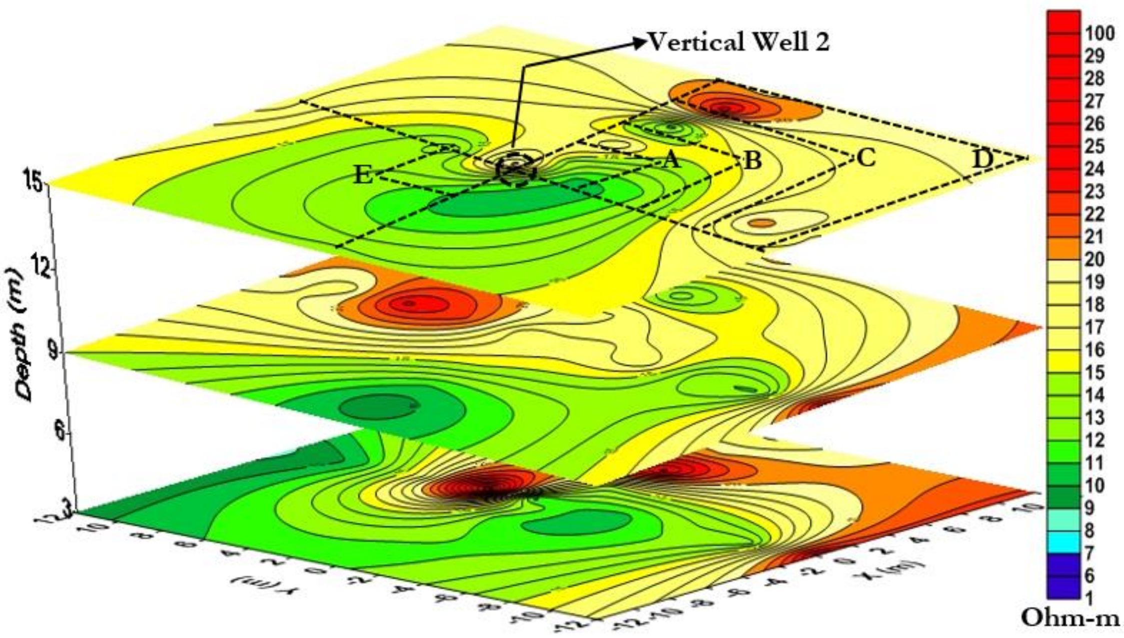
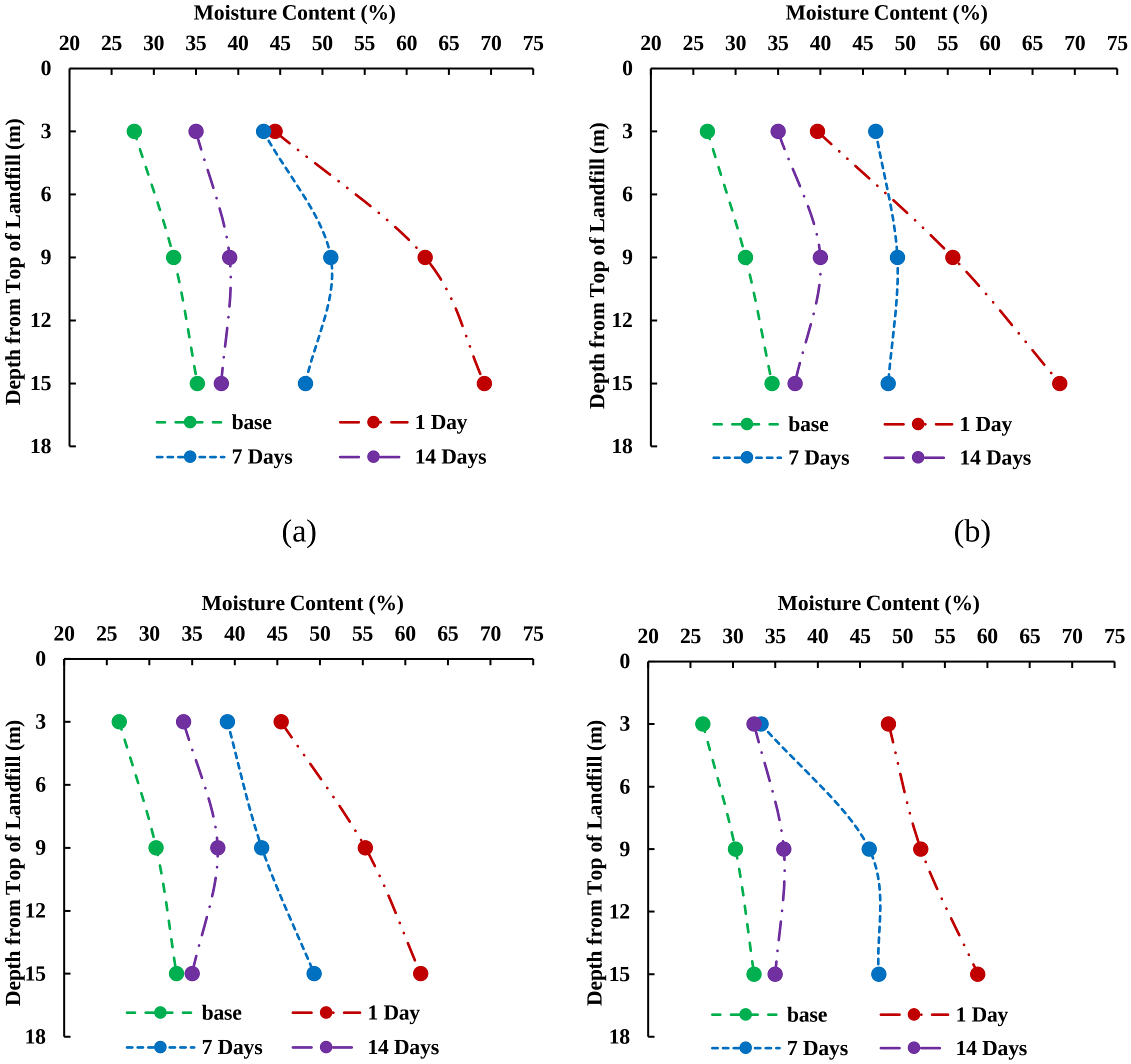


Figure 4.6 Schematic diagram for the points A, B, C, and D

Figure 4.7 shows the moisture content estimated from the correlation with resistivity (Shihada, 2011) for 1 day, 1 week (7 days), and 2 weeks (14 days) after recirculation. Based on the figure, the moisture content around the well after recirculation was higher than the initial baseline study, due to the addition of moisture through the vertical wells. The moisture content increased significantly after 1 day of recirculation and continued to spread around the vertical well up to 2 weeks. The waste mass around the well decomposed with the addition of moisture through the well, and the moisture content decreased, being used in the decomposition process. Therefore, following the initial increase in moisture content after 1 day of recirculation, the moisture content began decreasing and eventually returned to the initial moisture content before the addition of moisture. The moisture content after 2 weeks was lower than after 1 week, and 1 week moisture contents were usually found lower than 1 day after recirculation. A slight variation occurred due to the heterogeneity of the waste.

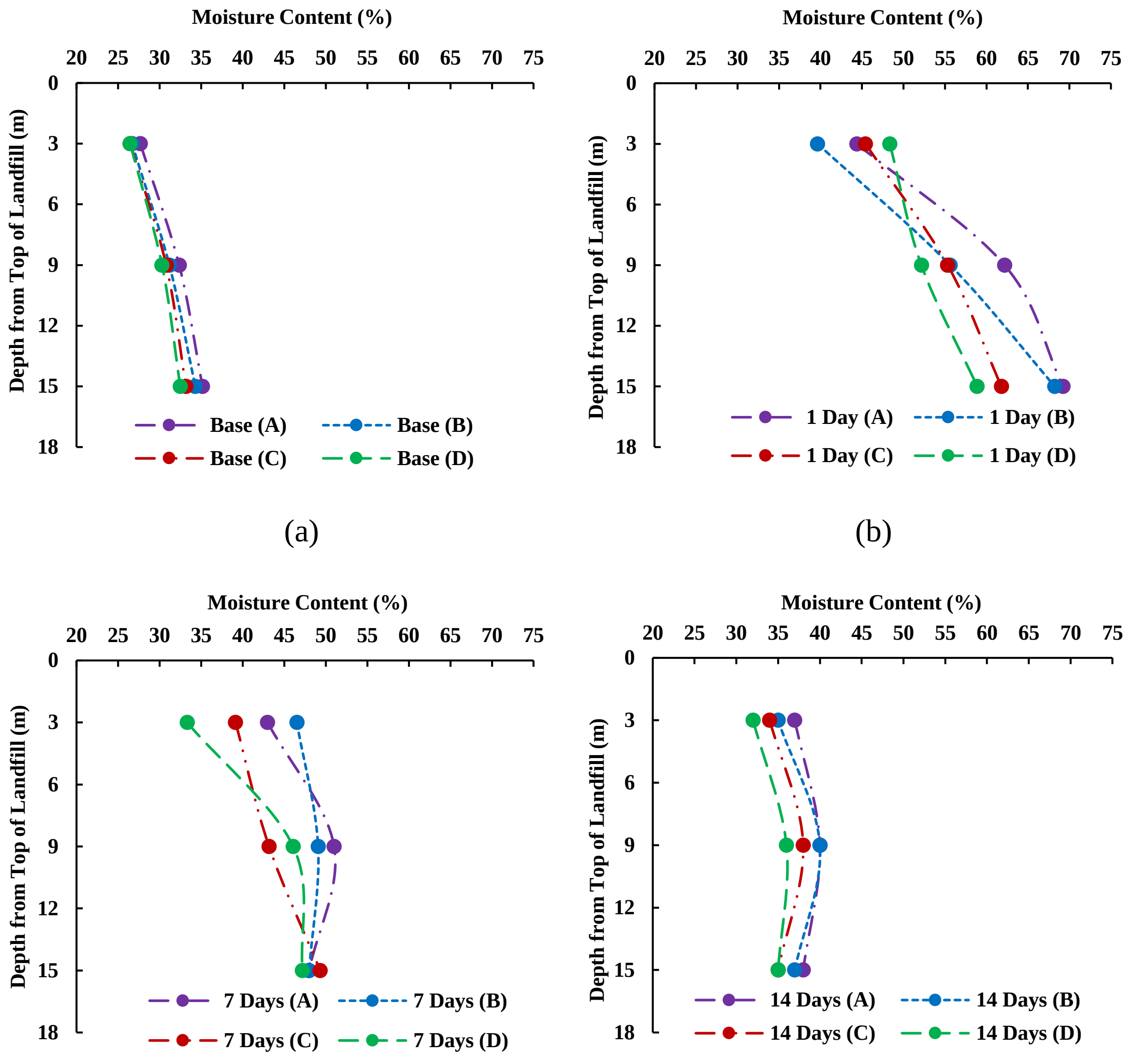


(a) (b)

(c) (d)

Figure 4.7 Moisture distribution with depth for first recirculation: (a) at point A; (b) at point B; (c) at point C; and (d) at point D

Figure 4.8 illustrates the comparison of moisture distribution with depth for different points (as shown in Figure 6) after recirculation.



(a) (b)

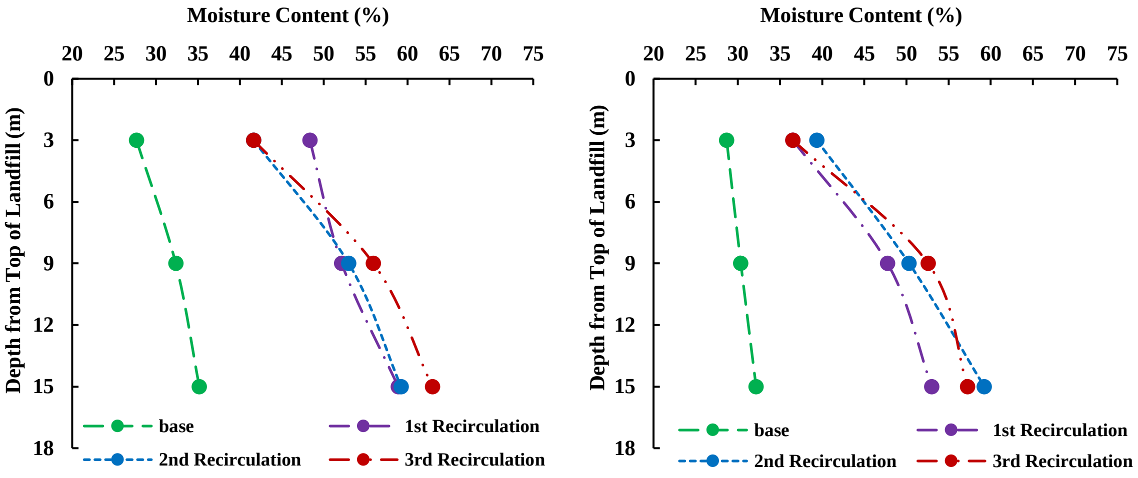
(c) (d)

Figure 4.8 Comparison of moisture distribution with depth for different points (a) base; (b) 1 day; (c) 7 days; and (d) 14 days

The results indicated that moisture distribution was almost identical to the baseline study. Point A was the closest and point D was the farthest distance from the vertical well. Hence, it is obvious that the moisture content will be higher at point A than at point D foe the same time period. The results show the expected trends for points A, B, C, and D for the same time.

Comparison of Different Recirculation

Three resistivity imaging tests were conducted for three different leachate recirculation to observe moisture distribution. ERI tests were performed at an interval of 1 day, 1 week (7 days), and 2 weeks (14 days) after each leachate recirculation. The recirculation amount was 45,800 liters (12,100 gallons), 32,500 liters (8,600 gallons), and 38,900 liters (10,300 gallons) for first recirculation, second recirculation, and third recirculation, respectively. The obtained results indicated identical behavior for each leachate recirculation, as illustrated in Figure 4.9. The identical results occurred due to uniform compaction, identical composition, and similar amounts of leachate recirculation. Figure 4.8 (on the previous page) represents moisture distribution after 1 day for three different examples of leachate recirculation for point A and point B. The baseline data for point A and point B shows slight variations, which indicate the presence of moisture at point B at the time of the baseline study. In both points, the moisture content varied from 27.7 to 62.9% with the increment of depth.



(a) (b)

Figure 4.9 Moisture distribution after 1 day of leachate recirculation: (a) at point A; and (b) at point B

Comparison of Results

Municipal solid waste is highly heterogeneous and anisotropic in nature where leachate flows as pore fluid. Variable field results may be obtained due to the heterogeneity and anisotropy of waste. As a result, it may be impossible to measure the representative values of the water content of municipal solid waste (Oweis et al., 1990; McCreanor, 1998). Thus, the presented field results may vary from other field and model results.

Khire and Mukherjee (2007) conducted a numerical study using finite-element model HYDRUS-2D to evaluate key design variables for leachate recirculation systems consisting of vertical wells in a bioreactor landfill. The design parameters were evaluated under steady-state flow conditions, which are rarely achieved in the field. A minimal effect of the well diameter, hydraulic conductivity of the well drainage pack, and screen height and screen depth of the well were observed on the wetted width of the waste for a given liquid flux. The wetted width and the injection pressure for a given liquid flux decreased with the increase in the hydraulic conductivity of the waste. The study evaluated the effect of dosing frequency for a leachate recirculation amount of 5.5 m^3/d on wetted width by simulating leachate injections for different durations, having hydraulic conductivity of 10^{-5} m/s and initial degree of saturation of the waste 25%. The result indicated that the required time for the wetted width (1.3 m to 1.9 m) reached constant value is 5 days.

Another numerical study using SEEP/W was performed by Jain et al., in 2010 to estimate key design inputs of vertical wells for liquid addition in bioreactor landfills. The study presents a series of design charts showing the dimensionless steady-state flow rate, lateral zone of impact, and the dimensionless liquid volume needed to reach a steady-state condition, as a function of dimensionless input variables. The study assumed homogeneous waste, steady-state conditions, zero resistance for air phase to liquid phase, and continuous operation (24 hours a day and 365 days a year) to simulate the model. In reality, all of the assumptions may not be possible in field conditions. Thus, the current field study is not compared with the model results.

Manzur et al., 2016 performed a field study, using ERI, on the leachate recirculation system at the City of Denton Landfill to monitor the extent of moisture variations in a bioreactor landfill. The results indicated that the recirculated leachate travels laterally between 11 m and 16 m.

CONCLUSIONS

Vertical injection wells are one of the major leachate recirculation systems currently implemented all over the world to operate bioreactor landfills. The current study was conducted at the City of Denton Landfill to monitor performance of vertical injection wells in a bioreactor landfill. The ERI technique was applied at interval of time to monitor moisture movement around the vertical well before and after leachate recirculation. The reduced resistivity contour around the vertical well represents the extent of leachate flow after leachate recirculation through the wells. Based on the results, the initial moisture content ranged from 31.5% to 36.5% before liquid addition around the wells. The moisture content after one day of leachate injection was observed from 49.50% to 64.60%, and decreased after one week of leachate injections, ranging from 40.12% to 47.03%. After two weeks of leachate injection, the moisture content ranged from 31.75% to 38.60%. The moisture zone increased with the addition of leachate and rebounded to its pre-existing state with the increment of time, due to leachate recirculation. Based on the results, the moisture content rebounded to its pre-existing state with the addition of leachate. Hence, the optimum frequency of leachate recirculation is almost 2 weeks (14 days) for a bioreactor/ELR operation using vertical wells. The RI data trends shows that the moisture added through the vertical wells spreads around the wells within two weeks and returns to its original moisture content after that. Therefore, based on the preliminary test results, vertical recirculation wells can be effectively implemented for moisture distribution within a bioreactor landfill.

CHAPTER 5

PERFORMANCE MONITORING AND EFFICIENCY EVALUATION OF A BIOREACTOR LANDFILL OPERATION

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ABSTRACT

The fundamental process involved in the operation of landfills as bioreactor or ELR landfills is the addition of water and/or the recirculation of leachate into the landfill's waste mass. The added moisture accelerates waste decomposition, enhances gas production, and increases waste stabilization. Although several benefits are associated with the bioreactor operation, limited studies have been conducted to monitor landfill performance. Landfill performance can be monitored by several indicators, such as moisture distribution, water balance, landfill settlement, and gas generation. Several studies have been conducted to monitor the bioreactor performance by individual parameters as performance indicators. However, to better asses the performance of bioreactor landfills, a combined assessment of operational parameters is required. Therefore, the objective of this current study is to monitor the performance of a bioreactor landfill operation, based on different operational parameters. The study was conducted at the City of Denton Landfill, Denton, Texas. Electrical Resistivity Imaging (ERI) was utilized to monitor moisture distribution in the landfill due to leachate recirculation or the addition of water in the landfills. The HELP model was also utilized to simulate the water balance in the landfill. Based on the HELP analysis and field results, it was observed the actual leachate generation in field was almost 55% lower than the HELP model results. The reason behind the lower leachate return from the landfill might be due to the added water/leachate being partially used in gas production. Hence, an increase in gas generation was observed, increasing from 543.6 m^3/h (320 scfm) in 2010-2011 to 1087.3 m^3/h (640 scfm) in 2014-2015. Moreover, in some locations of the landfill cell, in the 2014-2015 year, 4.7 ft. (1.43 m) maximum settlement was found, which also reflected the accelerated waste stabilization due to the bioreactor operation. Therefore, based on the results, it can be summarized that the bioreactor landfill operation performed efficiently with time.

INTRODUCTION

Modern engineered landfills have evolved to dispose of municipal solid waste (MSW) with reduced environmental impacts from contaminants and to maintain federal regulations. However, the concept of a municipal solid waste (MSW) landfill is primarily based on a permanent storage and containment or “dry cell.” In recent years, there has been an increased understanding of the process of landfill decomposition, which has established a trend to shifting the concept of landfill design from the permanent storage towards a bioreactor or “wet cell’-approach (Maurer, 1994; Krol et al., 1994). A bioreactor landfill, where leachate or additional water is recirculated using a recirculation system, is an alternative approach to the conventional landfill. According to Cheremisinoff and Morresi (1976), a bioreactor operation not only avoids leachate treatment, but also enhances waste degradation and gas generation. A landfill is considered a bioreactor landfill if i) design and/or operational practices are associated with leachate recirculation and/or the addition of supplemental liquids, or ii) the landfill owner adopts some concerted methods to accelerate decomposition (Bareither et al., 2010). Several studies have been conducted to monitor the bioreactor landfill performance by individual parameters (i.e., moisture distribution, water balance, gas generation, and landfill settlement) as performance indicators. However, limited studies have been conducted on the effect of combining different parameters to assess the performance of a bioreactor landfill. Therefore, the objective of this current study is to monitor the performance of a bioreactor landfill operation based on different operational parameters.

BACKGROUND

Landfill performance usually depends on several factors which contribute to the effective operation of a landfill. According to the study conducted by Bureau et al. (2005), the bioreactor performance depends on the design of the leachate collection system, variable quality of the injected leachate, and the monitoring time. This study also describes the importance of water balance on the effective operation of a bioreactor landfill. Several studies have shown other influential factors on performance evaluation, including slope stability, liner and final cover integrity, landfill gas production and emission, and landfill settlement (EPA, 2006; Morris and Barlaz, 2011; Bareither et. al., 2010; EPA, 2005). Schubeler (1996) showed that the effective management of MSW is critical for public health and well-being, and sustainability of the urban environment. In a bioreactor landfill operation, additional or supplemental water/leachate is added through a leachate recirculation system. The ability of leachate recirculation to enhance the biodegradation process has been widely investigated by several researchers (Maier et al., 1995; Van den Broek et al., 1995; Yuen et al., 1995; Ham and Bookter, 1982; Blakey et al., 1997). Additionally, leachate recirculation promotes the landfill stabilization through effective moisture distribution and maintaining optimum moisture contents, resulting in a more effective transfer of microbes and nutrients throughout the waste mass.

Efficient moisture distribution provides an appropriate environment for the growth of nutrients and microbes that enhance the biodegradation of MSW. Several studies have reported that the enhanced degradation of MSW in bioreactor landfills, due to leachate recirculation, depends on uniform and efficient moisture distribution (Sharma and Reddy, 2004; Reddy, 2006; ITRC, 2006; Reddy et al., 2009). In 2012, Kulkarni and Reddy described the following advantages of the enhanced degradation process due to efficient moisture distribution: 1) accelerates landfill gas production, 2) improves feasibility of waste-to-energy projects, 3) increases landfill settlement that minimizes post-closure monitoring costs, 4) reduces or eliminates on-site or off-site leachate treatment costs, 5) hastens landfill stabilization, and 6) reduces the threat to public health and the environment.

Efficient moisture distribution can be better achieved with the understanding of the water balance in the landfill. The general concept of water balance is that water input is equal to the summation of water output (leachate return, runoff) and water storage from the landfill. According to Blight (1996) and Lu et al., (1985), the water balance equation for a landfill is expressed as: Water input to landfill = Water output + Water stored.

The main input components to landfill are precipitation and leachate recirculation; whereas, outputs are runoff, evapotranspiration, and lateral drainage (leachate generation). A portion of the input water is utilized by the waste decomposition and soil moisture storage. According to Farquhar (1989), water balance can be measured by using the following equation:

$$PERC = P - RO - ET - \Delta S + G$$

Where

PERC = Percolation; P = Precipitation; RO = Runoff; ET = Evapotranspiration; ΔS = Soil moisture storage; G = Infiltration of groundwater

Another equation used to conduct water balance, given by Alslaibi et al (2013), is as follows

$$L = P + J - R_{off} - AET - U_w$$

Where

L = Lateral drainage; P = Precipitation; J = Leachate recirculation; R_{off} = Runoff; AET = Actual evapotranspiration; U_w = Soil moisture storage.

The leachate generation from landfills can be estimated through the water balance equations presented above.

While the addition of liquid aids in faster degradation and stabilization of landfills, one of the major concerns remains estimated settlement. Estimation of settlement is necessary and very crucial for the application of post-closure final cover. From the operator's point of view, the capacity of the landfill will be increased due to the settlement that occurred at the time of filling. Large post-closure settlement may have adverse effects on surface ponding, crack development, and cover system failures, which cause maintenance problems. The landfill settlement progresses almost 30%-40%, over a long period of time, compared to the initial height of the landfill (Ling et al., 1998).

According to the Jesserberger and Kockel (1991) study, several factors, i.e., waste types, composition, compaction methods, and rate of decomposition affect the unit weight, void ratio, and landfill settlement. The prediction of settlement of MSW is quite difficult by using the consolidation theory for soil, as MSW is not fully saturated and has heterogeneous properties. However, a monitoring and observational system can be a vital tool for predicting landfill settlement. Landfill settlement is associated with the waste volume reduction, and the compression of waste occurs mainly due to waste decomposition, but also to self-weight, overburden pressure, and external loads. The waste decomposition occurs due to biological and chemical processes, and causes a large reduction of waste volume. Several researchers have conducted studies on landfill settlement and presented their results (Merz and Stone, 1962; Rao et al., 1977; Sowers, 1973; Dodt et al., 1987; and Coduto and Huitric, 1990). The landfill settlement that is associated with the degradation of MSW over time has special importance in determining air space, final cover systems, and interim design, as well as on planning the vertical expansion of existing facilities (Hossain and Gabr, 2005). Sowers (1968 and 1973) stated that physiochemical and biological changes of waste, distortion and reorientation of the refuse, erosion of the fine material into a large void, and long-term creep processes are the significant factors that have an effect on waste compressibility. The study also concluded that the waste settles 10 to 30 percent due to its own weight, within one to two years after placement. The operation of the bioreactor landfill includes leachate recirculation and the addition of supplemental water that enhances gas production and changes leachate quantity and quality. This operation system has a significant impact on the geotechnical compressibility properties, settlement rate, and magnitude of the buried waste (Hossain and Gabr, 2005).

Leachate recirculation and the addition of supplemental liquids are the most common strategies to enhance decomposition of solid waste by stimulating microbial activity (Pohland, 1975; Barlaz et al., 1990; Pacey et al., 1999; Reinhart et al., 2002; Mehta et al., 2002; Warith, 2002; Benson et al., 2007; Bareither et al., 2008a). The specific objectives of this practice are to maximize waste decomposition that contributes to air space recovery and gas production and to minimize off-site leachate treatment cost (Pohland, 1996; Miller and Emge, 1997; Reinhart et al., 2002; Morris et al., 2003; Benson et al., 2007). The rate of settlement increases with the addition of leachate over time. The rate of time-dependent waste settlement is approximately 1.6 times larger in a bioreactor landfill than in a conventional landfill, due to bio-degradation (Bareither et al., 2010).

MSW generates a tremendous amount of landfill gas due to decomposition of MSW over time. Landfill gas generation is a biological process, where decomposition of organic waste occurs with microbial growth. The principal gases are produced due to degradation of the organic fraction of municipal solid waste. The principal landfill gas production from cellulose can be expressed by a simple equation, as follows.

$$C_6H_{10}O_5 + H_2O \longrightarrow 3CH_4 + 3CO_2$$

Landfill gas generation consists of five different phases. Phase I is the aerobic decomposition and starts just after placement of the solid waste into the landfill. In this stage, no methane is generated, and decomposition continues until the depletion of entrained oxygen. According to EMCON (1998), aerobic decomposition may occur from 6 to 18 months, depending on the waste placement in the bottom of the landfill. In Phase II, decomposition starts due to aerobic/acid formation, and methane generation begins because of methane-forming bacteria. Phase III is the transition-to-aerobic stage, where both methane and carbon dioxide concentration stabilize. Phase IV starts as an anaerobic condition, where methane and carbon dioxide reach their maximum values and begin to reduce. Phase V is the final stage of decomposition, and no more degradation occurs.

Landfill gas is composed of several components, in which methane and carbon dioxide are the main constituents. Waste heterogeneity, landfill operation, and environmental conditions play an important role in gas generation variability (Yesiller et al., 2008; Samir, 2014). Landfill gas generation is affected by several factors that enhance waste decomposition and gas production. According to EMCON (1998) and McBean et al., (1995), decomposition and gas production continue over time and take a very short period of time. The study also cited other affecting factors, such as waste decomposition, moisture content, waste particle size, age of waste, pH, temperature, and others.

METHODOLOGY

Site description

The study and data were collected from The City of Denton Landfill, which is located on Mayhill Road, in Denton, Texas. The landfill was built in 1984 and immediately started receiving waste from the city, according to the permit, and operated as a conventional landfill. In 2009, the landfill received permission from the Texas Commission on Environmental Quality (TCEQ) to operate as a bioreactor or enhanced leachate recirculation (ELR) landfill. This landfill receives approximately 700 tons of waste per day. The landfill has seven cells. Cell 1590A (cell 0) is a conventional cell, and the rest of them are bioreactor landfill cells, as presented in Figure 5.1. The study was mainly conducted in cell 2 to monitor the performance of the bioreactor operation.

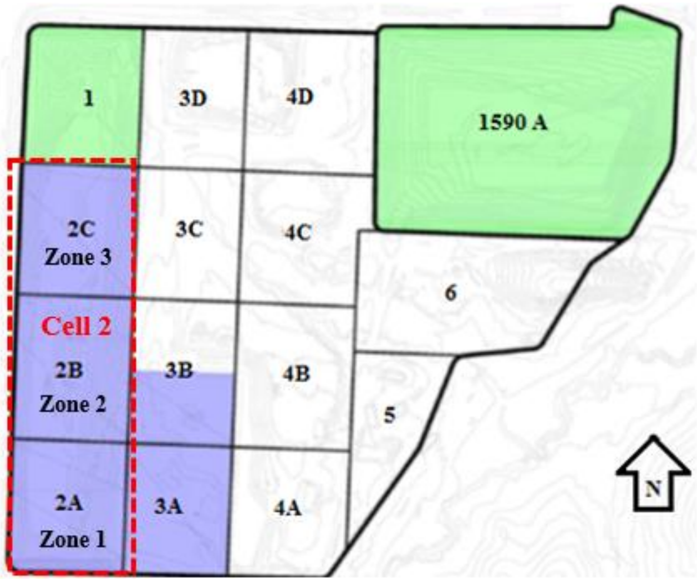


Figure 5.1 Cell configuration of the City of Denton MSW landfill

Selection of horizontal recirculation pipe and vertical injection well locations

The City of Denton Landfill has 35 horizontal recirculation pipes in Cell 2 to recirculate water or leachate into the landfill. Cell 2 was divided into three zones: Zone 1, Zone 2, and Zone 3. The locations of the horizontal pipes are presented in Figure 5.2. As a part of the study, horizontal recirculation pipes H2 and H16 were selected, based on the maximum recirculation through each pipe, to monitor moisture distribution, using the electrical resistivity imaging (ERI) method. No recirculation pipes were selected from Zone 3 in this current study. Lines A-A’, B-B’ and C-C’ in Figure 5.2 represent the field ERI test lines.

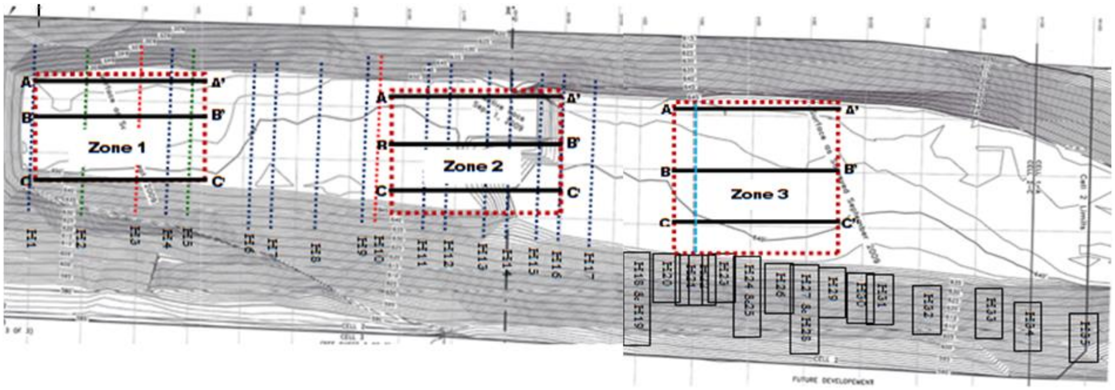


Figure 5.2 Horizontal pipes and zone at Cell 2

In addition, three vertical injection wells were located at Cell 2 to inject water/leachate into the landfill. For the research purpose, vertical injection well 2 was selected, based on maximum injection through a single well, to observe moisture variation using the ERI method. The layout of vertical injection well 2 and the ERI lines is presented in Figure 5.3.

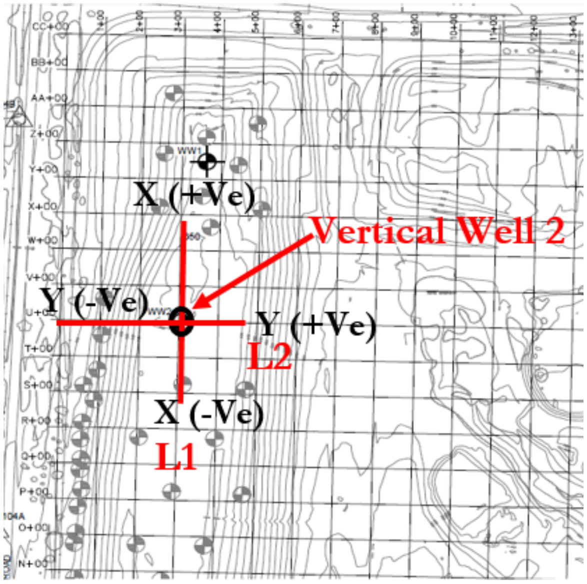


Figure 5.3 Layout of vertical injection well 2 and ERI lines at Cell 2

Experimental Plan

Different methods were utilized to monitor the operational parameters to assess the performance of the bioreactor landfill. Each method was used to observe a specific performance indicator of landfill operation, as presented in Table 5.1.

Table 5.1 Different Methods Applied in Landfill

Method	**Application**
Electrical Resistivity Imaging (ERI)	Moisture Distribution
Visual HELP	Leachate Generation
Surveying	Settlement

ERI Method

Electrical resistivity imaging (ERI) is a non-destructive geophysical technique which is utilized to explore subsurface information. The method primarily works on the principle of Ohm's law, where a current is delivered to the soil or waste material, and the resulting potential difference is measured. Several researchers have utilized the ERI technique in geophysical and geo-environmental evaluations (Hossain et al., 2010; Dahlin, 2001; Gueguen and Palciauskas, 1992; Shihada, 2011; Kibria, 2014; Abu Hassanein et al., 1996; McCarter, 1984; Michot et al., 2003; Goyal et al., 1996; Ozcep et al., 2009; and, Guerin et al., 2004; Griller et al., 2012).

Visual HELP

Visual HELP is the most recently developed hydrological evaluation tool for designing landfills. It is an advanced version of HELP 2.01, and is used for predicting leachate generation and evaluating potential leachate contamination. Visual HELP can i) graphically create several profiles representing different parts of a landfill, ii) automatically generate statistically-reliable weather data (or create your own), and run complex model simulations, iii) visualize full-color, high-resolution results, and iv) prepare graphical and document materials. The program has a built-in database for synthetic weather data and 42 common landfill materials, similar to HELP 2.01. However, the visual HELP provides a graphical interpretation for better understanding of leachate generation and lateral drainage of leachate.

Surveying

Handheld GPS (ProMark 200) was used to measure the landfill subsidence as a part of surveying for Cell 2 and Cell 3 in the City of Denton Landfill. The device measures latitude, longitude, and azimuth of every point. The elevation is calculated from the value of azimuth, which indicates the settlement/subsidence of the point.

RESULTS AND DISCUSSION

Moisture distribution, leachate generation, gas production, and settlement were monitored for performance and efficiency evaluations. The obtained results of the performance indicators are included in this section.

Moisture Distribution due to Leachate Recirculation through Horizontal Pipes

The study was conducted from the year May 2009 to April 2012 to observe moisture distribution inside the landfill. An Initial base 2D electrical resistivity imaging test line was performed across each pipe before leachate recirculation, as shown in Figure 5.3. ERI tests were also performed at intervals of one day, one week, and two weeks after leachate recirculation to detect moisture distribution with time. Figure 5.4 represents the ERI results for the baseline (before recirculation), 1 day after recirculation, 1 week (7 days) after recirculation, and 2 weeks (14 days) after recirculation.

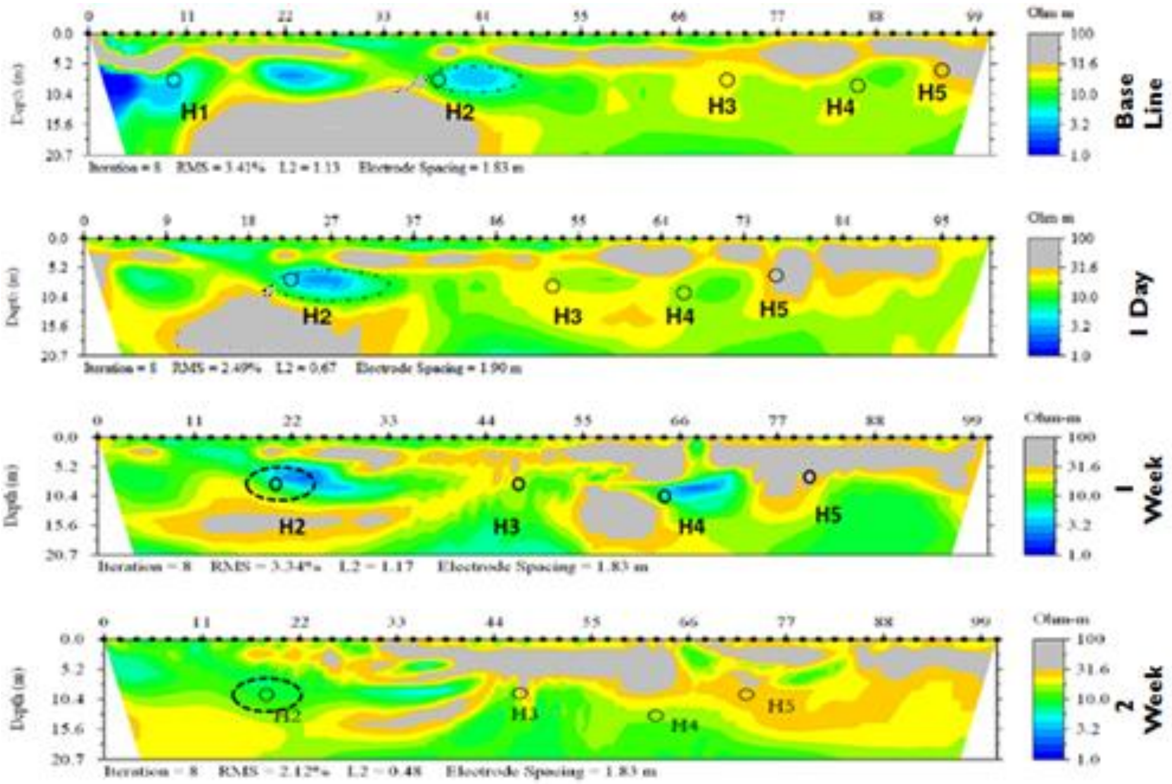
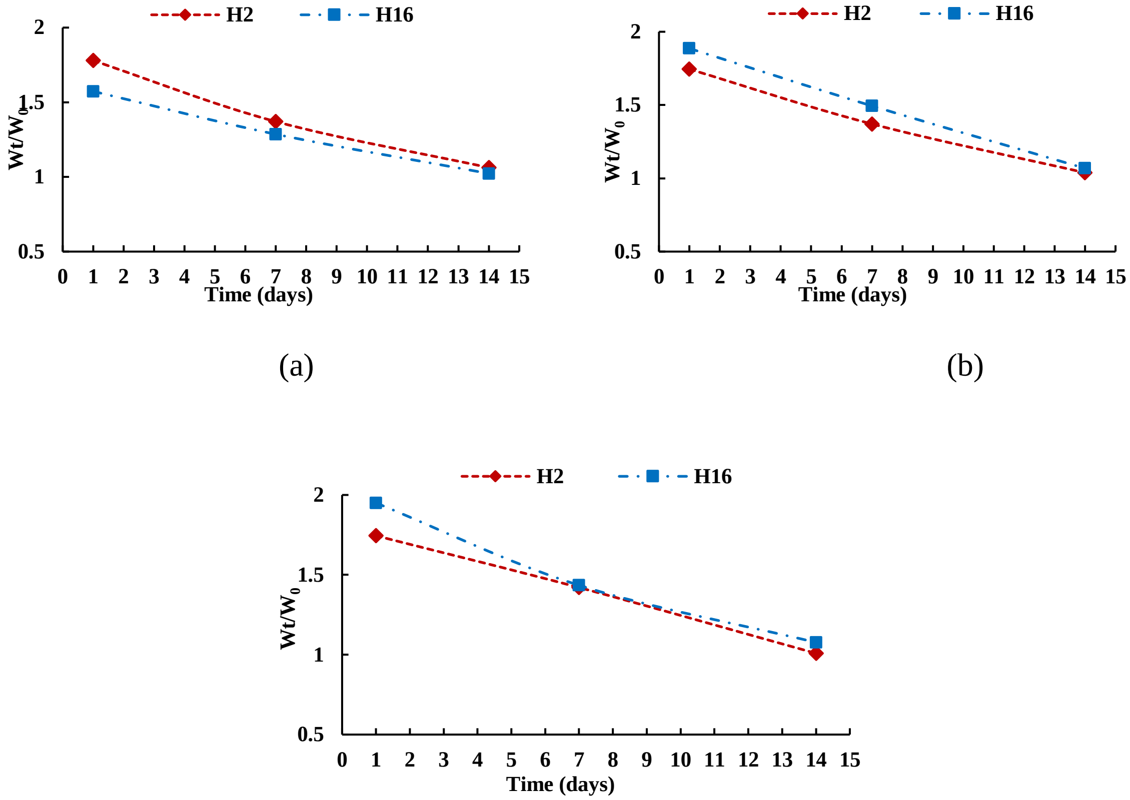


Figure 5.4 Resistivity imaging results of pipe H2 for the first year, May 2009 to April 2010

A significant high-resistivity gray zone was observed near pipe H2 in the baseline study. The ERI results, after 1 day of leachate recirculation, indicated the presence of a low resistivity blue zone and a decrease of the high-resistivity area. The low-resistivity zone expanded and the high-resistivity area further decreased after 7 days of leachate recirculation. The ERI results of 14 days after leachate recirculation showed mostly green and yellow areas, which have moderate resistivity value. The variation from baseline to 14 days was due to moisture movement (horizontal and vertical), leachate generation, and waste decomposition with time.

The moisture content was estimated from the ERI results, using a previously developed equation (Shihada, 2011). The estimated moisture content was further analyzed to determine moisture distribution with time. The moisture content of selected pipes H2 and H16 was plotted for 3 years and indicated a decreasing trend with time, as shown in Figure 5.5.



(a)

(b)

(c)

W$_0$ = Moisture content with baseline study; W$_t$ = Moisture content with time.

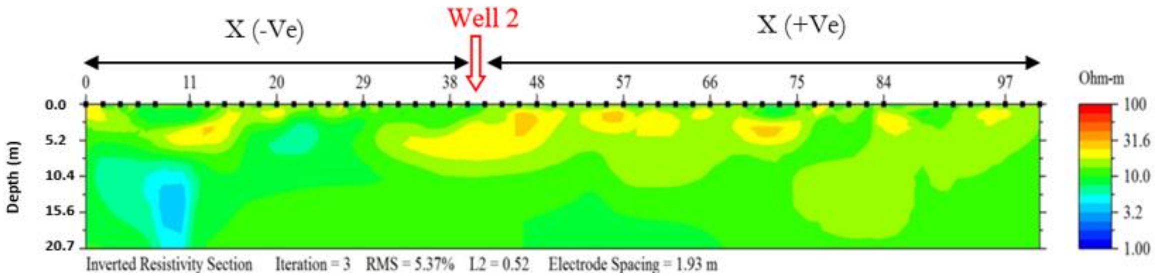
Figure 5.5 Moisture content ratio with time: (a) first year: May 2009 to April 2010, (b) second year: May 2010 to April 20111, and (c) third year: May 2011 to April 2012.

Moisture content increased significantly after one day of leachate recirculation, and the observed moisture content ratio ranged from 1.5 to 2.0. The RI values increased with time after 7 days of leachate recirculation compared to 1 day of RI values, due to distribution and usage effects, and the determined moisture content ratio ranged from 1.21 to 1.50. Finally, the moisture content ratio was close to 1.0 after 14 days of leachate recirculation, because distribution and usage were almost complete. The results indicated that the moisture content rebounded to its pre-existing position after 2 weeks (14 days) of leachate recirculation. The distribution and usage of added leachate or water takes time due to the compaction, heterogeneity of waste, and slow degradation process effects.

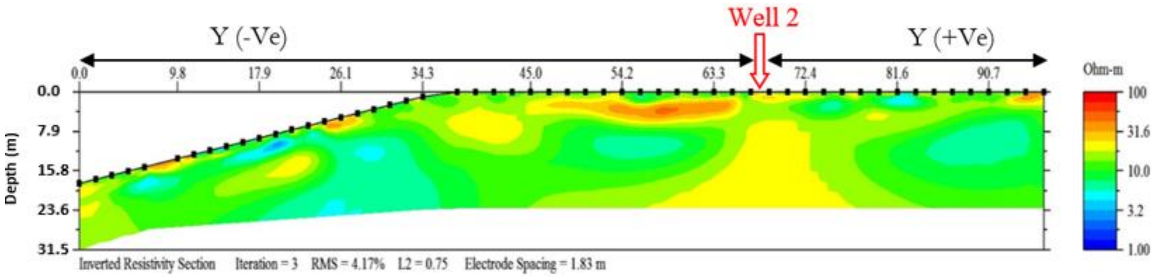
Moisture Distribution due to Leachate Recirculation through Vertical Injection Well 2

A 2-D electrical resistivity imaging test was conducted to determine moisture flow and accumulation within the solid waste due to the leachate recirculation or water addition through vertical injection well 2. A total of 2 resistivity lines were conducted in "+" pattern around the well to observe the moisture distribution with time. In each direction, a minimum distance 15.24 m (50 ft.) was maintained from the center of the well to perform the test, as this was the distance that Manzur et al (2016) reported.

Moisture distribution can be identified by the low resistivity contours around the well. ERI tests were performed, as a baseline, for the vertical well 2 before any leachate injection. The analyzed baseline results are presented in Figure 5.6. Since no leachate was recirculated through vertical well 2 before the baseline studies, the influence area indicated a low moisture zone around the well. It was observed from the distribution profile that the resistivity values were 23.5 and 20.8 ohm-m at a depth of 3 m for baselines L1 and L2, as presented in Figure 5.6 (a) and Figure 5.6 (b), respectively.



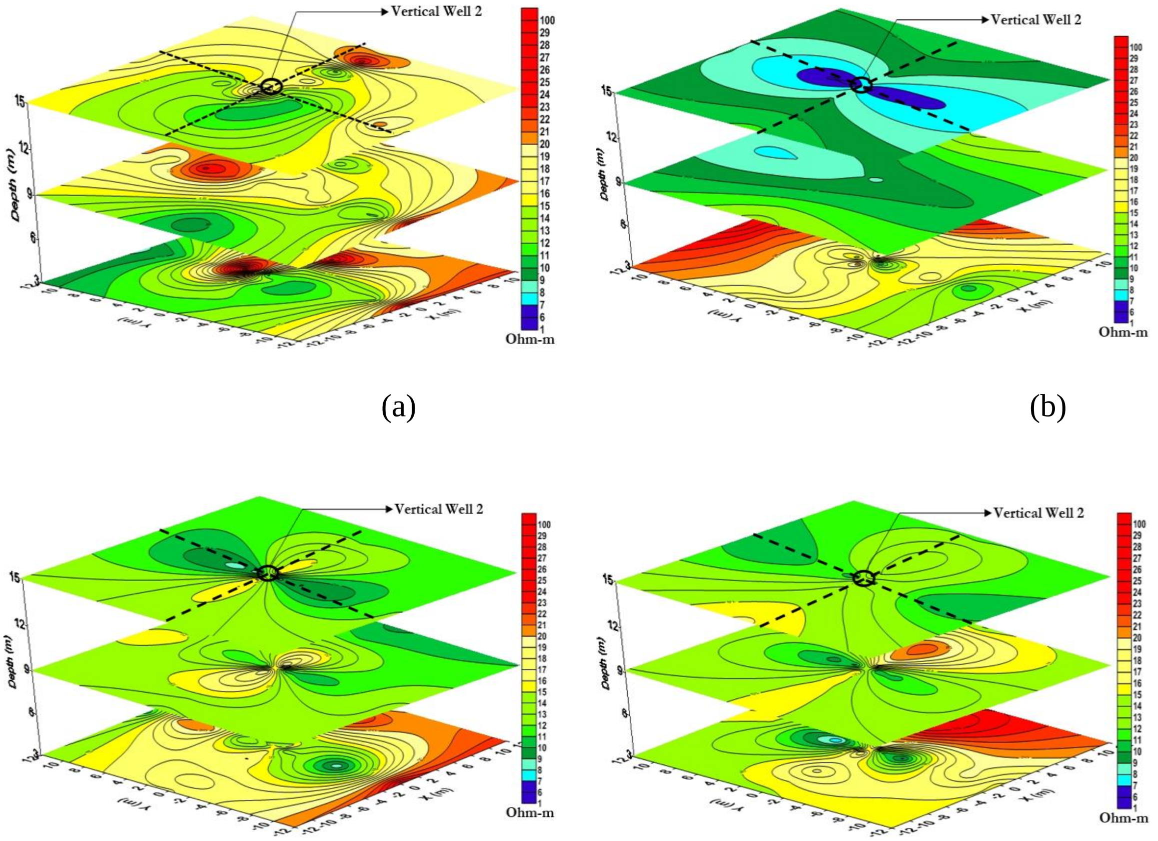
(a)



(b)

Figure 5.6 RI baseline for the vertical well 2: (a) line L1, and (b) line L2

The 2D ERI results were further analyzed by 3D plotting, using Surfer. Line 1 and line 2 were taken as X-axis and Y-axis, and the resistivity value was taken as the Z-axis, to plot the 3D diagram. Figure 5.7 represents the 3D RI results, which had 3 slices, i.e., top, middle, and bottom. The slices were taken from the top of the landfill, in which depths of 3 m, 9 m, and 15 m were used to cut the bottom, middle, and top slice. The baseline result presented in Figure 7(a) indicates that the most of the area around the pipe had high RI values, ranging from 12 to 25 ohm-m, indicating a low moisture zone.



(a) (b)

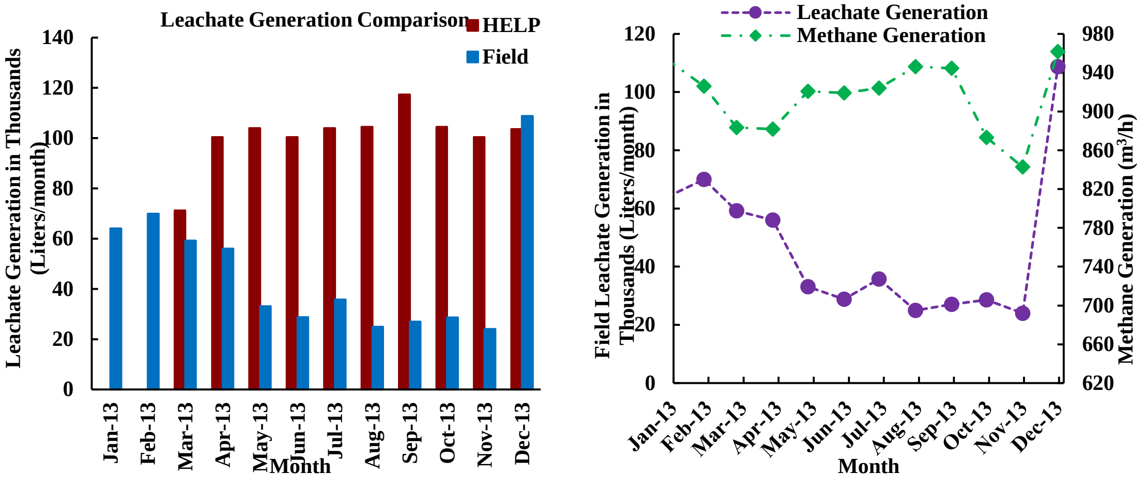
(c) (d)

Figure 5.7 Moisture distributions at different depths: (a) baseline study, (b) after 1 day, (c) after 1 week (7 days), and (d) after 2 week (14 days) of leachate recirculation.

A total of 12,100 gallons of leachate were recirculated through vertical injection well 2 on 07/21/2015. The RI lines were conducted at intervals of 1 day, 1 week (7 days), and 2 weeks (14 days) after leachate recirculation on 07/22/2015, 07/28/2015, and 08/04/2015, as presented in Figure 7 (b, c, and d). The result after 1 day indicates that the RI values decreased around the pipe at each depth, due to the low amount of spreading and usage effects. The result showed that RI values ranged from 7 to 15 ohm-m, which represents a low moisture zone due to the effect of leachate injection through the vertical well. The RI values after 7 days increased, compared to 1 day of RI values, as a fraction of it was utilized for decomposition, and the rest of the leachate moved laterally and vertically, and then travelled towards the bottom liner. Spreading, usage, and leachate generation were almost complete after 14 days, as the RI values rebounded to those of the baseline study.

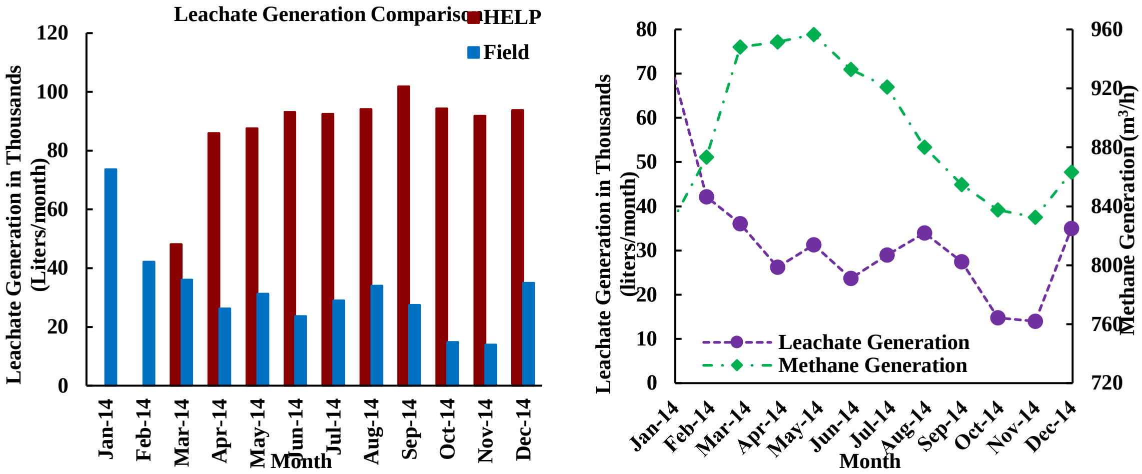
Leachate and Gas Generation

Generated leachate was collected form the City of Denton Landfill for the year 2103 to 2015. The Visual HELP program was utilized to model the water balance for the City of Denton Landfill to predict leachate generation. Different climactic conditions, types of precipitation, temperature variations, and cover types were considered to represent a wide range of water balance, primarily the percolation rate, surface runoff, and lateral drainage. Three separate models were designed in 2013, 2014, and 2015, to determine the amount of leachate generation. The analyzed results for the years 2013, 2014, and 2015 are shown in Figures 5.8 (a, b); 5.9 (a, b); and 5.10 (a, b), respectively. There was no leachate generation during the first two months of each year because HELP does not generate leachate for the first two months. The comparison of field leachate generation with the HELP model in each year, as presented in Figures 5.8 (a),5. 9 (a), and 5.10 (a) indicated that the value of the model was always higher than that of the field results, except for December, 2013. The reason for this discrepancy was that the leachate recirculated was almost 2.5 to 3 times higher in that specific month. The difference between HELP and the field results indicate that some part of injected leachate is used up by the waste mass for degradation. In a bioreactor landfill, added moisture generally aids the waste decomposition and produces methane. As a result, leachate generation and methane production should have a reciprocal correlation, in which less leachate generation causes more methane production. Leachate and methane generation are compared and presented in Figures 5.8 (b), 5.9 (b), and 5.10 (b) for the years 2013, 2014, and 2015. The observed results indicate the expected trend, where, in each month, a smaller amount of leachate generation indicates a higher amount of methane production, and vice versa.



(a) (b)

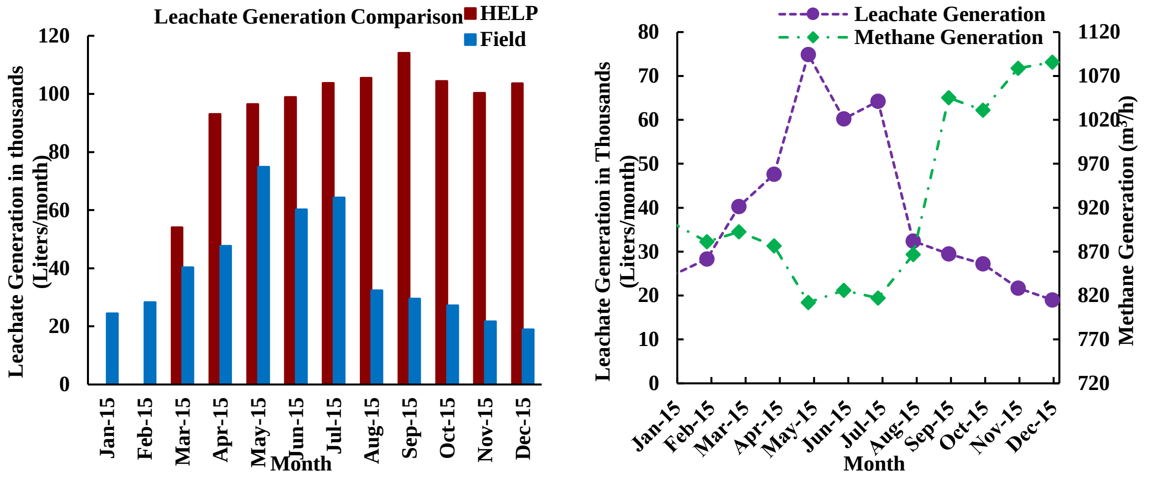
Figure 5.8 Field leachate generation comparison with: (a) HELP model, and (b) methane generation for the Year 2013



(a)

(b)

Figure 5.9 Field leachate generation comparison with: (a) HELP model, and (b) methane generation for the Year 2014



(a)

(b)

Figure 5.10 Field leachate generation comparison with: (a) HELP model, and (b) methane generation for the Year 2015

Based on the gas production data collected from the City of Denton Landfill for Cell 2, the maximum amount of gas production in a single year increased from 543 m^3/h (period of 2010-2011) to 1087 m^3/h (period of 2014-2015) over 5 years of bioreactor landfill operation. Gas production for the first year period, 2010-2011, was lower compared to other periods due to the low amount of waste degradation; whereas, the amount of gas production increased significantly from 2011-2012, due to increased waste degradation. Moreover, energy generation from landfill gas is directly related to the gas production. The generated energy serves households, providing energy according to their needs. Currently, the City of Denton Landfill serves 1600 households by providing electricity produced from the collected gas. In the near future, more than 3000 households will be served by the City of Denton Landfill.

Settlement and Additional Space Gain

Landfill settlement can result from a number of causes, including waste decomposition, primary consolidation, secondary consolidation, and reduction in void space inside the waste mass. Landfill sites require frequent monitoring to maintain safe landfill operations. The settlement of the City of Denton Landfill has been monitored by collecting annual subsidence survey data since January, 2010. The survey is conducted annually to determine the change of elevation due to the solid waste decomposition caused by leachate recirculation. The City of Denton Landfill authority collects the data by using a handheld GPS at the selected locations. The subsidence of the landfill studied at Cell 2 for the years of 2010 to 2015 is presented in Figure 5.11.

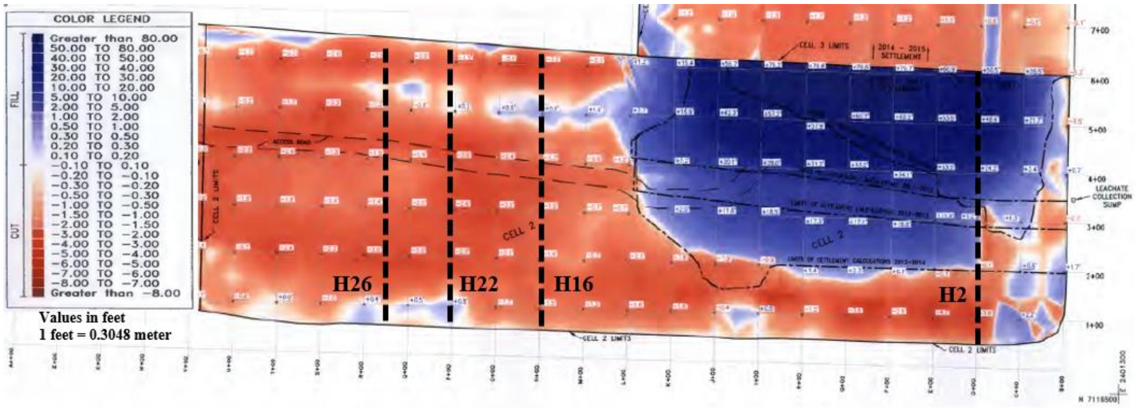
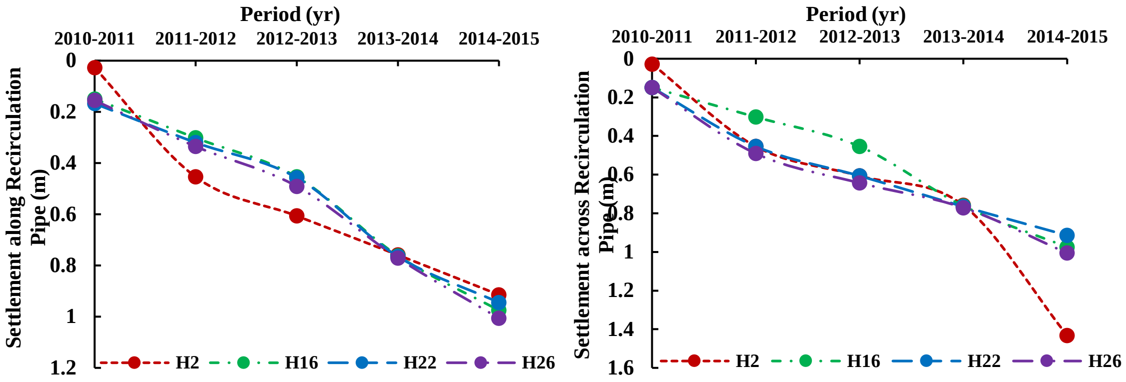


Figure 5.11 Landfill subsidence from 2010 to 2015 at Cell 2

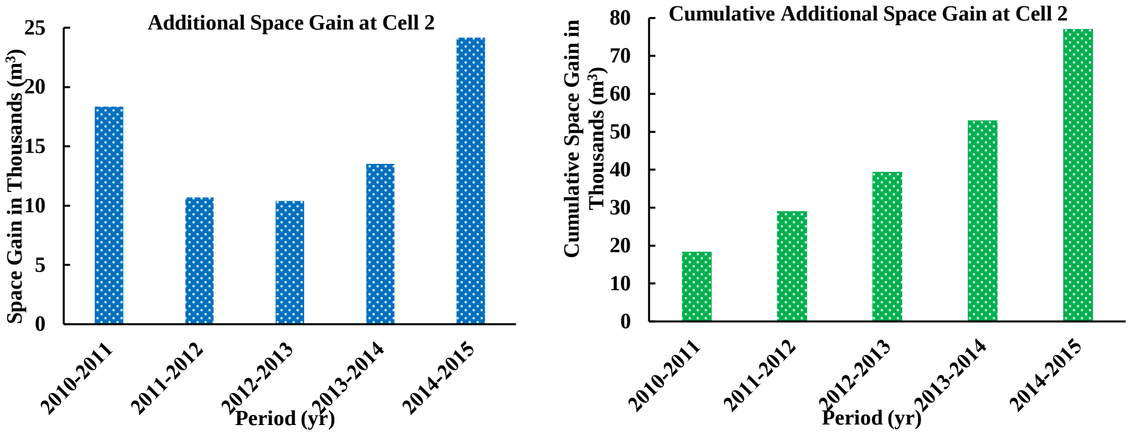
The subsidence data along recirculation pipes indicates that the landfill settlement increased with time, from 0.03 m to 1.10 m within 5 years of leachate recirculation, as shown in Figure 5.12 (a). Similar trends were observed for the subsidence data across recirculation pipes, where settlement ranged from 0.03 m to 1.45 m, as presented in Figure 5.12 (b). This similarity shows horizontal movement of added leachate within the waste mass. A very few non-uniform settlements of the MSW along and across recirculation pipes indicate the heterogeneity of waste materials. The readily-degradable components (mostly paper, foot waste, and yard waste) begin decomposing soon after the waste placement; whereas, the slow-degrading materials (wood, cloth fibers) may take a longer time to decompose, even with the presence of moisture added through leachate recirculation. The maximum amount of subsidence was observed across recirculation pipe H2, in which the maximum amount of leachate was recirculated. Results indicate that the settlement has increased every year, proving that the bioreactor landfill operation is working efficiently.



(a) (b)

Figure 5.12 Change in elevations: (a) along, and (b) across recirculation pipes of Cell 2

The additional space gained for each period from 2010-2011 to 2014-2015 was compared, as presented in Figure 5.13 (a). The amount of space gained in 2010-2011 was higher than in 2011-2012, because the void space decreased inside the waste mass due to overburden pressure and waste decomposition. Figure 13(a) shows that the amount of space gained for the periods of 2011-2012 and 2012-2013 was almost identical, due to slow degradation and reduction of the remaining void space. The additional space gain in Cell 2 increased significantly after the third year period due to more rapid waste degradation. Figure 5.13 (b) represents the cumulative additional space gain, which indicates that the total amount of additional space gain was 77,000 m^3 from five years of the bioreactor operation. This air space recovery is one of the major advantages of bioreactor landfill operations, as the space can be utilized for future landfill operations.

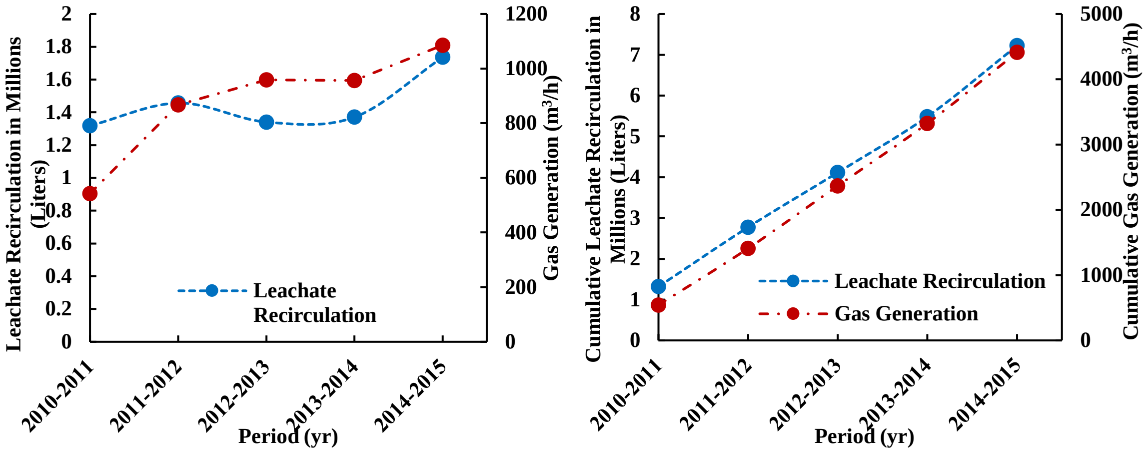


(a) (b)

Figure 5.13 Additional space gain due to settlement: (a) each period, and (b) cumulative

Effect of Leachate Recirculation on Gas Production

Leachate recirculation helps microbial growth inside the landfill, enhancing waste decomposition over time. Gas production accelerates significantly with time due to waste degradation. Leachate recirculation and gas production data was collected from the City of Denton Landfill to analyze their effects on each other. Figure 5.14 (a) represents the comparison between leachate generation and gas production for each period. The gas production value increased significantly from the first year to the fifth; whereas, the third and fourth year periods showed the same amount of gas production. The reason is due to the sudden drop in leachate recirculation for the third year period. The cumulative comparison between leachate generation and gas production is presented in Figure 5.14(b), which indicates that the trend of efficient bioreactor operations is increasing. The results indicate that the maximum gas production is possible through maximum leachate recirculation (within the regulation limits).

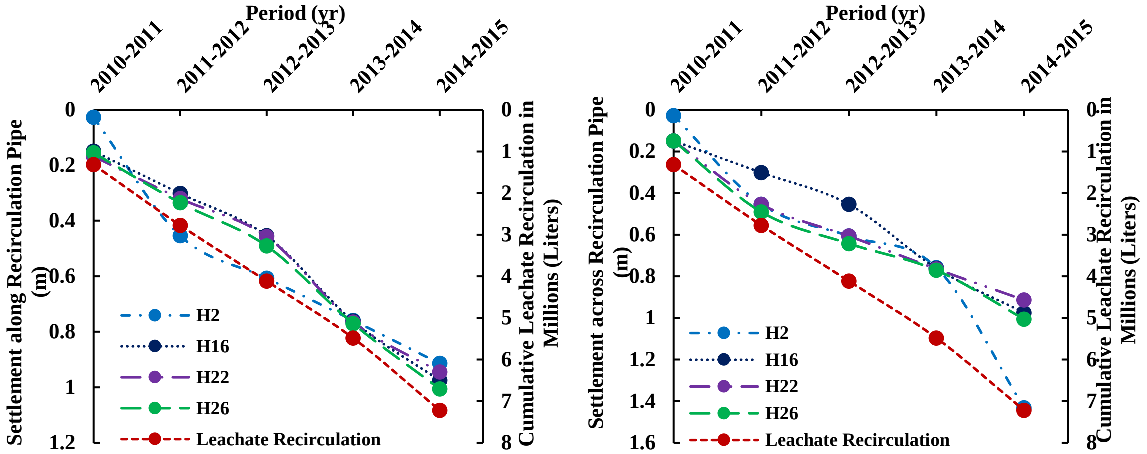


(a) (b)

Figure 5.14 Comparison between leachate recirculation and gas production: (a) each period, and (b) cumulative

Effect of Leachate Recirculation on Settlement

Settlement of landfill is directly related to the leachate recirculation, which provides an ambient environment for the growth of microbial organisms. Microbial activity decomposes waste particles into small ones, to produce gas, and eventually minimizes the pore space inside the waste. Figure 5.15 (a and b) represents the comparison between leachate recirculation and settlement. The results indicate that the settlement, along and across recirculation pipes, increases with the increments of cumulative leachate recirculation. The results depict that the maximum settlement is possible through maximum leachate recirculation (within the regulation limits).

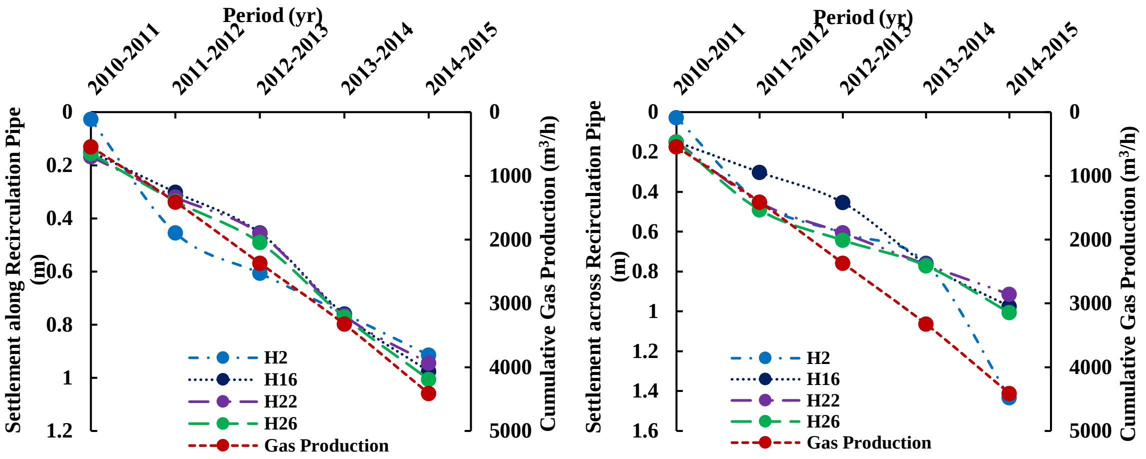


(a) (b)

Figure 5.15 Relationship between leachate recirculation and settlement: (a) along recirculation pipe, (b) across recirculation pipe

Effect of Gas Production on Settlement

Gas production in a bioreactor landfill occurs due to the effect of additional moisture, which enhances decomposition of waste. More gas production indicates more waste degradation that decreases waste volume over time. The comparison between cumulative gas production and settlement for each year presented in Figure 5.16 (a, and b). The results indicate that the settlement along and across recirculation pipes increases with the increment of cumulative gas production. The results show that the maximum settlement occurs with the maximum gas production.



(a) (b)

Figure 5.16 Relationship between gas production and settlement: (a) along recirculation pipe, (b) across recirculation pipe

Finally, an evaluation table was developed based on the summarized results as shown in Table X. Moisture distribution, application frequency of leachate, gas production, settlement, and leachate generation was mainly considered for the table. The purpose of this evaluation table is to utilize in future to predict the performance of other bioreactor landfill operations.

Table 5.2 Evaluation Table of Performance Indicators

Indicators	Period				
	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Moisture Distribution	Working Efficiently				
Recirculation Frequency	14 Days				
Settlement (m)	0.24	0.45	0.72	1.05	1.45
Gas Production (m^3/h)	543	865	957	953	1087
Leachate Generation (liters/month)	82116	60465	70931	54695	63557

CONCLUSIONS

The current study was conducted to monitor the performance of bioreactor operations and evaluate the efficiency of a bioreactor landfill. Cell 2 of the City of Denton Landfill, where additional water/leachate is recirculated into the landfill, was selected for the study. The study evaluated the moisture distribution, leachate generation, gas production, and waste settlement as individual and combined performance indicators. All the performance indicators were monitored and evaluated extensively to determine the efficiency of the bioreactor landfill. The following conclusions are based on the results of the study:

1. Leachate recirculation influences the moisture distribution around the horizontal recirculation pipes. The moisture increases significantly after 1 day of leachate recirculation, then starts decreasing after 1 week (7 days), and rebounds to its initial condition after 2 weeks (14 days).

2. The ERI results for vertical wells indicate a similar trend of moisture distribution around the water injection well.

3. The leachate generation data shows that the leachate return from the field is less compared to that of the HELP analysis, which might be explained by the higher gas yield due to leachate recirculation.

4. The gas production data indicates an increase in generation from 543 m^3/h (320 scfm) in 2010-2011 to 1087 m^3/h (640 scfm) in 2014-2015, which is the effect of waste decomposition due to leachate recirculation.

5. The maximum settlement observed was 1.45 m (4.8 ft.) in year 2014-2015 due to the bioreactor operation, which reflects accelerated waste degradation and enhanced gas production.
6. An evaluation table was developed to utilize in future to evaluate the other bioreactor landfill performance.

The obtained results of the performance indicators indicate that gas generation and settlement increase significantly with time due to leachate recirculation and efficient moisture distribution. Therefore, based on the performance monitoring and efficiency evaluation, it can be concluded that a bioreactor operation works efficiently over time.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Moisture distribution is the main criteria for the effectiveness of a bioreactor operation, and it leads to more rapid waste degradation, enhanced gas production, and a gain of air space. It also minimizes the time that it takes for the waste to decompose, and shortens final cover monitoring. A bioreactor operation can be assessed by employing several performance indicators, such as leachate generation, gas production, and landfill settlement. In addition, the effect of combined indicators is important to the evaluation of bioreactor performance. The existing literature is lacking in its explanations of the effect of efficient moisture distribution and the combination of performance indicators to assess effective bioreactor operation.

Municipal Solid Waste (MSW) is a heterogeneous material, which creates problems for consistent moisture distribution. The uniform compaction level of MSW in the field is tough to attain and hinders the effective moisture flow path. In addition, daily cover produces channelization for the added liquid, which creates a non-uniform moisture flow path. Therefore, monitoring moisture distribution in landfill is essential to an effective operation. In this study, leachate was recirculated through horizontal recirculation pipes and vertical injection wells. The moisture distribution was monitored, using the Electrical Resistivity Imaging (ERI) method before and after leachate recirculation, at different time intervals.

Efficient moisture distribution causes the operation of a bioreactor landfill to be efficient and effective. The effective operation is also directly related to the performance indicators, i.e., leachate generation, gas production, and landfill settlement. The collected data from the City of Denton Landfill was analyzed and evaluated with time to observe and determine whether the operation was efficient. The combination of performance indicators were also analyzed and evaluated to estimate their combined effect on the effective landfill operation.

Based on the obtained results in this study, the following conclusions were drawn.

A bioreactor landfill has advantages over a conventional landfill in terms of enhanced waste decomposition and gas production due to leachate recirculation or moisture addition.

Cell 2 of the Denton Landfill was divided into three zones to perform ERI tests. Five horizontal recirculation pipes (H2, H16, H18, H22, and H26) were selected, based on maximum leachate recirculation through a single pipe, to observe moisture distribution with time.

The ERI tests were performed before and after leachate recirculation at different intervals (of one day, one week, and two weeks) to evaluate the effect of time on moisture distribution. The reduced resistivity contour around the pipe represented the flow of leachate after leachate recirculation through the pipe.

Moisture content was estimated around the leachate recirculation pipes, from the field ERI results, using an equation developed by Shihada, 2011.The estimated results indicated that the initial moisture content for the baseline was 31.5% before any leachate/recirculation adjacent to the recirculation pipe.

The moisture contents after 1 day, 1 week (7 days) and two weeks (14 days) after leachate recirculation were found to be 49.52%, 40.48%, and 31.74%, respectively.

The moisture content decreased with time after recirculation and rebounded to its initial state after two weeks (14 days) of leachate recirculation. Therefore, it can be concluded that optimum frequency for leachate recirculation for an effective bioreactor operation is two weeks (14 days).

The vertical injection well 2 at Cell 2 was selected, based on maximum leachate recirculation through a single well, and moisture distribution was monitored using ERI tests. Based on the estimated results, the initial moisture content ranged from 31.5% to 36.5% before leachate injection. Within one day after leachate injection, the moisture content was observed from 49.5% to 64.6%. After one week of leachate injection, the moisture content decreased and ranged from 40.12% to 47.03%. After two weeks of leachate injection, moisture content ranged from 31.75% to 38.6%.

The RI data trends shows that the moisture added through the vertical wells spread around the wells within two weeks and returned to its original moisture content after that. Therefore, from preliminary test results, it can be concluded that vertical recirculation wells can be effectively implemented for moisture distribution within a bioreactor landfill. According to the leachate generation data, leachate returned from the field is less than that of the HELP analysis, which might be explained by the higher gas yield due to recirculation of the leachate.

Gas production data demonstrates a surge in generation from 543 m^3/h (320 scfm) in 2010-2011 to 1087 m^3/h (640 scfm) in 2014-2015, which indicates enhanced waste decomposition due to leachate recirculation.

During 2014-2015, the maximum settlement observed was about 1.43 m (4.7 ft.), which indicates accelerated waste degradation and enhanced gas production due to the bioreactor operation. One of the outcomes from the evaluation of the performance indicators is that gas generation and settlement increases significantly with time due to leachate recirculation and efficient moisture distribution. Therefore, a conclusion can be drawn, based on the performance monitoring and efficiency evaluation, which the bioreactor operation is working efficiently over time.

The conducted research work provides a general understanding of bioreactor landfill operations. Leachate recirculation and performance indicators play vital roles in their effective operation. A limited understanding of the overall process may lead to an inefficient operation of bioreactor landfill. The specific contributions of this research are:

Development of generalized field frequency curve, which will help to estimate time intervals of leachate recirculation to operate bioreactor landfills efficiently. This curve will also determine approximate moisture content without doing resistivity imaging at the field.

Development of a general scenario of moisture distribution due to leachate recirculation through horizontal recirculation pipes and vertical injection wells, which will assist with the efficient operation of a bioreactor landfill.

Establishment of a general understanding of influential factors should be assessed when evaluations the performance of bioreactor landfill operation.

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