ASSESSMENT OF LEACHATE COLLECTION SYSTEM CLOGGING AT FLORIDA MUNICIPAL SOLID WASTE LANDFILLS

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LIST OF ACRONYMS

AASHTO	American Association of State Highway Officials
ASTM	American Society of Testing and Materials
COD	Chemical Oxygen Demand
FDEP	Florida Department of Environmental Protection
FDOT	Florida Department of Transportation
GR	Gradient Ratio
HDPE	High Density Polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
LCS	Leachate Collection System
LDS	Leak Detection System
MSW	Municipal Solid Waste
PE	Polyethylene
PVC	Polyvinyl Chloride
QA/QC	Quality Assurance/Quality Control
RCRA	Resource Conservation and Recovery Act
SDR	Standard Dimension Ratio
UCF	University of Central Florida
UF	University of Florida
USGS	United States Geological Survey

ABSTRACT

Leachate collection systems (LCS) are designed to efficiently remove leachate from a landfill. This prevents ponding on the liner system and ultimately leachate migration into the environment. The permeability of the leachate collection system is a primary factor in determining the collection efficiency. The potential of the drainage materials (sand, gravel, and geotextiles) to clog as a result of biological growth and particulate clogging is an important issue that should be addressed in landfill design.

Two distinct efforts were required to assess the potential for bio-clogging of LCSs at Florida Landfills. A University of Florida (UF) effort examined the extent of clogging that had occurred in an MSW landfill LCS that had been in operation for six years. Research conducted at the University of Central Florida (UCF) compared LCS designs and safety factors at existing Florida landfills to recommended design practices and safety factors.

The excavation of the Putnam County Landfill's LCS provided an opportunity to collect drainage materials which had been exposed to landfill conditions for six years. Analysis of these materials indicated that clogging played a minor role in the reduction of flow through the drainage media. Calculations indicated that clogging mechanisms generated a minimal increase in the leachate head on the liner. The structural collapse of the LCS manholes was the primary factor impacting collection efficiency.

Surveying landfill designers and FDEP Officers as well as assessment of existing Florida landfill designs indicated that in general, Florida landfill LCSs are well-designed, state-of-the-art facilities. However, analysis of existing Florida LCS configurations suggested safety factors ranging from 0.025 to 0.1 which have been associated with less than optimal long-term LCS performance. Both designers and regulators expressed concerns over clogging of the LCS components but, material deterioration has not been addressed in past designs.

A field study incorporating several state-wide test cells was recommended to quantify the effects of individual clogging mechanisms.

LIST OF KEYWORDS

Landfill Design
Leachate Collection System
Permeability
Geotextile
Biological Clogging
Chemical Clogging
Safety Factors

EXECUTIVE SUMMARY

1. INTRODUCTION

Groundwater has been shown to be the primary contaminant release route at problematic landfills. The leachate collection system (LCS) is the ultimate barrier between the environment and landfill leachate and is thus subject to intense scrutiny during both the design and installation phases. The Florida Department of Environmental Protection (FDEP) requires a bottom liner for all municipal solid waste (MSW) landfills in Florida. The FDEP, in compliance with RCRA-subtitle D regulations, has variable head requirements ranging from one inch to one foot depending on the design of the liner system. These maximum heads are design standards and it is presumed that the performance of a LCS designed based on these heads will not violate the FDEP or RCRA regulations.

The drainage system, located above the liner, is perhaps the most critical element of the collection system, and generally consists of highly permeable natural materials such as sand or gravel or a geosynthetic net. The drain must be protected by a natural soil or geosynthetic filter to order to minimize clogging. Research at several northeastern landfills has shown that the ability of the LCS to remove leachate from the landfill may significantly deteriorate over time due to clogging of the drainage materials used in the LCS. Koerner and Koerner (1991) concluded that the filter should be the focus of concern in the leachate collection system because of a reduction in permeability over time. Filter clogging results from sedimentation, biological growth, chemical precipitation and/or biochemical precipitation, and is quite difficult to control. Clogging is most often experienced during the acidogenic period when organic substrates and precipitating metals such as calcium, magnesium, iron, and manganese are most highly concentrated in the leachate. Florida’s hot, humid climate may provide more optimum conditions for biological growth in the LCS resulting in a greater potential for LCS failure.

Two distinct efforts were required to assess the potential for bio-clogging of LCSs at Florida Landfills. A University of Florida (UF) effort examined the extent of clogging that had occurred in an MSW landfill leachate collection system that had been in operation for six years. Research conducted at the University of Central Florida (UCF) compared LCS designs and safety factors at existing Florida landfills to recommended design practices and safety factors.

2. FLORIDA LANDFILL DESIGN SURVEY

2.1 Methodology

The goals of this project were met by surveying landfill designers and regulators and by collecting design information on the LCSs in existing Florida landfills.

Design engineers were surveyed to collect information on the following: the estimation of leachate loading rates, design head employed, preferred liner system, collection pipe spacing, type of leachate collection pipe used, the slope of the drainage length, slope of the leachate collection pipe, materials generally used, maintenance requirements, and safety factors used.

Landfill regulators were contacted to collect information on the following: the standard design head required, LCS maintenance requirements, leachate loading calculation, preferred design equations, quality control, and safety factor requirements.

General design information collected on existing Florida LCSs included LCS configuration, collection pipe spacing, type of leachate collection pipe used, the slope of the drainage length, the slope of the leachate collection pipe, and material specifications for existing Florida LCSs. This information was gathered by contacting landfill owners directly and reviewing landfill designs on file at the Tampa, Orlando, and Jacksonville FDEP offices.

2.2 Survey Results

A summary of the information collected is presented below.

2.2.1 Florida DEP Representatives

A one-foot (30-cm) leachate head was considered standard by all of the offices. The estimation of leachate arrival to the LCS, the method used to determine pipe spacing, and the selection of the LCS configuration were considered to be completely up to the discretion of the design engineer. Some representatives preferred the use of the HELP model for determination of leachate loadings and determination of pipe spacing. The use of safety factors in the design of the LCS was an ambiguous issue. Common answers to the question, “Are factors of safety required for any of the LCS components?” were “I don’t know, the design engineer decides this.” and “Safety factors are recommended but not required.” Despite the lack of interest in safety factors, clogging of the LCS components was universally considered to be a concern although the exact clogging mechanisms were disputed. One representative felt that clogging of the LCS was a result of chemical reactions due to paper mill wastes while another representative in a different district suggested that clogging may not be the result of biological activity alone.

The use of specified materials in the construction of the LCS is ensured by a third party QA/QC program as well as by site visits by FDEP officials.

Requirements for maintenance (back flushing) of the LCS varied significantly among the districts. Two districts called for maintenance only in the event that clogging of the LCS was suspected while others required semi-annual or annual back-flushing of the system. Two representatives indicated that video taping of the LCS pipes was required. Of these two representatives, one required yearly video taping of the LCS pipes while the other required video taping during permit renewals.

2.2.2 Designers

Surveying landfill design firms produced a wealth of information on the general techniques and assumptions used to design LCSs. Designers indicated that the most strongly regulated design variables were the head on the liner and permeability of the clay barrier. They also commented that the design of the pipe system; particularly size, settlement, flexibility, and mechanical strength; was important.

All of the firms employed HDPE liners in the LCS. Those designers who specified a thickness all indicated 60 mil. Two of the firms indicated they use double liners exclusively.

The use of perforated leachate collection pipes was specified by all of the firms while ‘socking’ of the pipe with a geotextile was indicated by only one firm. The preferred drainage materials were a geonet/sand system, river rock, or crushed stone. The filter layer was either a geotextile (usually a non-woven) or a sand layer. The firms were evenly split on the use of geotextiles in the LCS. The firms which employed geotextiles used them as part of the gravel envelope surrounding the collection pipe. One firm indicated that while they preferred to use geotextiles, there were cases where the owner or regulator was strongly opposed to them and they were not used. The use of biocide-treated geotextiles was indicated by only one firm.

Of the firms surveyed, only one indicated that no safety factors were used in the design of the LCS. However, of the remaining firms, three applied safety factors only to the design of the leachate collection pipes and not to the drainage materials. The two firms utilizing safety factors in design of the drainage materials, used either the HELP model with a 150% safety factor applied to the head on the liner or the safety factor technique proposed by Koerner et al. (1994) with an anticipated permeability loss of two orders of magnitude. When questioned about past design and installation problems, only two firms indicated troubles with the LCS. In both cases, the mechanical crushing of the LCS pipes was the cause of the LCS failure. Corrugated and PVC pipes were cited by one firm as being particularly susceptible to crushing.

All but one of the designers recommended regular flushing of the LCS pipes. Back-flushing was recommended at least annually. One firm recommended semi-annual back-flushing. The firm that did not recommend regular flushing did specify that the pipes should be cleaned by water jetting when poor system performance was observed. It is interesting to note, that all designers feel that LCS maintenance is important but that regulatory opinions on LCS maintenance varied significantly.

2.2.3 Landfill Designs

The design of the LCS of 25 of the 66 Class I landfills in Florida was analyzed. The design date of the landfills ranged from 1986 to 1997. A considerable increase in the detail and complexity of design was noted as time passed. Twelve of the landfills utilized a double liner system, the remainder utilized a composite liner system. The majority of the landfills evaluated used 60-mil HDPE liners in the LCS. Two of the landfills constructed in the late ‘80s (1986 and 1989) utilized 30-mil PVC liners. One of these landfills utilized the liner only on the side slopes of the LCS. The bottom liner consisted of 1 ft of 10^{-8} cm/s permeability clay over 2 ft of 10-7 cm/s permeability clay. Double liner systems used 60-mil HDPE liners for both the primary LCS and the leak detection system.

The majority of the landfills (64%) utilized 8 inch perforated HDPE collection pipes. All but one of the remaining designs used 6 inch perforated HDPE collection pipes. The one remaining landfill constructed in 1986 used a 4 inch perforated PVC collection pipe. The leak detection systems utilized either a 4-inch or a 6-inch perforated HDPE collection pipe. It is important to note that all of the designs evaluated used perforated rather than slotted pipes which are generally felt to be more susceptible to clogging. Also, none of the pipes used were corrugated pipes which were indicated by one designer to be susceptible to mechanical crushing.

All of the designs utilized a drainage envelope around the collection pipe consisting of a high permeability drainage material, usually large rock, wrapped with a geotextile. One of the designs had initially indicated socking the collection pipe but, this was changed prior to approval of the design. The fact that no 'socked' collection pipes were found, is encouraging. As was noted in the Koerner et al. study above, socking of the collection pipes results in extremely large drainage correction factors which translates to very low factors of safety. Enclosure of the collection pipe within an gravel/geotextile envelope commonly used in Florida LCSs results in safety factors ranging from 0.1 to 0.025. These safety factors are lower than recommended but are much better than the socked pipe scenario ($FS \cong 10^5$).

Seventy-six percent of the landfill designs reviewed incorporated a geonet-sand drainage layer. A large, coarse material such as river rock or gravel was used as the drainage media in the remaining designs. Material specification requirements on the design plans varied significantly. Most designs provided some material quality information usually a material type and permeability specification (i.e. sand, $K=10^{-3}$ cm/s). Some designs specified materials using AASHTO and FDOT material groups while others simply specified a general material type (i.e. sand, gravel, crushed rock). The use of AASHTO and FDOT material specifications is most likely the best policy to ensure that placed materials are equivalent to the materials required by the designer. Materials in these classifications can be directly purchased and field verification would generally consist of a simple sieve test for particle size distribution. The use of permeability specifications would dictate laboratory testing of the materials used to ensure that the installed and stipulated materials are equivalent.

2.3 Conclusions

The review of landfill regulator and designer surveys as well as discussions during TAG meetings produced the following conclusions and observations.

- Both regulators and designers have expressed concerns over clogging of the LCS components. However, material deterioration has not been addressed in designs in the past.
- HELP model-based LCS designs are driven by the open cell condition where all precipitation is received directly by the LCS.
- Traditional, equation based, designs use a lower than regulated maximum head as a safety factor.
- No designers supported 'socking' the leachate collection pipes and no existing LCSs evaluated utilized 'socked' pipes.

- The permeability of LCS materials may deteriorate over time, however, the amount of leachate received by the LCS will also decrease over time due to placement of final or intermediate caps.
- Concern was expressed that many designers are not familiar with the use of geotextile filters in LCSs and may be using them improperly. Geotextiles should be employed as material separation devices and not as a drainage material.
- In designs which incorporate geonets, our surveys showed that the effect of overlying materials (sand or geotextiles) on the transmissivity of the geonet was properly accounted for using manufacturer provided design information. However, the deterioration of this material which can be expected was not addressed.
- A geotextile study conducted at the Orange County Landfill in Orlando, Florida indicated that the geotextile with the largest initial open area ultimately had the lowest permeability most likely due to clogging.
- Design equations presume uniformly distributed precipitation which is not the case and presuppose the location of the maximum head. Both of these assumptions underestimate the actual performance of the LCS.
- The verification of LCS material quality during construction is done through visual inspection and testing. However, third party quality control is generally expensive and is not required or regulated.
- Maintenance of the LCS, generally flushing once or twice per year, is recommended by most designers however, regulatory requirements vary significantly and the LCS is usually only serviced once a problem has been identified.
- Sites which practice regular back-flushing of the LCS experience increased leachate flows after the back-flushing operation. Work conducted by Koerner and Koerner, (1990) suggests that this increase is most likely due to clearing of the pipe perforations rather than impacting the LCS materials.
- The assessment of existing Florida landfill LCS designs indicates that in general, Florida landfill LCS are well-designed, state-of-the-art facilities. Evaluation of the LCS configuration demonstrated that an envelope consisting of gravel wrapped in a geotextile was used to protect leachate collection pipes. This configuration results in worst case safety factors ranging from 0.1 to 0.025 depending on the exact site dimensions, much less than the recommended order of magnitude. Safety factors in this range have been demonstrated by Koerner et al. (1994) to be associated with less than optimal long-term leachate collection system performance.
- These results indicate that there is the potential for failure due to clogging of the geotextiles in Florida LCS. The exact degree to which Florida's unique climate impacts the potential for LCSs failure is impossible to estimate. Until a more complete understanding of the effect of particle transport, biological growths, and precipitation mechanisms on clogging is reached, a definitive appraisal is difficult.

3. FIELD STUDY OF AN OPERATING LANDFILL

3.1 Methodology

This section describes the process the process involved in sample collection. Incorporated into this discussion is a description of the excavation site, rehabilitation methods, and an explanation of sampling techniques.

3.1.1 Site Description

The landfill evaluated in this study was constructed in 1991. A single composite liner consisting of 20 cm of clay and a high density polyethylene HDPE geomembrane was used to line 8.1 ha (20 acres). The leachate collection system consisted of a saw tooth trench system with HDPE collection pipe wrapped (socked) directly with geofabric in the trenches. It should be noted that the practice of wrapping pipe directly with fabric is discouraged in today's landfill designs. The entire landfill bottom was overlain by 0.6 m (2 ft) of clean sand mined on site. Manholes were placed inside the perimeter of waste fill. The landfill was originally designed for expansion so that a total of 16 manholes would eventually be constructed. A total of eight were in place at the time of this study

In 1996, landfill operators noticed that leachate was backing up within the manholes of the leachate collection system. Inspection revealed that sections of the manholes were collapsing and allowing drainage sand, cover soil, and waste into the LCS, thus blocking the pipes. The manholes used in the original construction of the landfill consisted of flexible walled polyethylene (PE) that was added in sections as the waste was deposited. Use of this type of construction is not standard practice in modern landfills. A plan was developed to repair the faulty LCS. The project required the excavation of each manhole down to the liner. Thus, an opportunity was offered to examine the condition of the drainage material in the LCS in the areas surrounding the manholes. Both drainage sand and geofabric were available for collection.

3.1.2 Sample Collection

Excavation of the leachate collection system began in summer 1997. Waste was excavated from the vicinity of the manholes using a track hoe. The depth of waste removed from the surrounding areas of each manhole varied from 2.0 to 7.0 m (6.5 to 23.0 ft). As waste was excavated, individual sections of the manhole were removed until the geomembrane (upper section of the liner system) was reached. Dewatering of the excavated areas inhibited the excavation process. A typical cross-section of the original manholes is presented in Figure 4.3.

The rehabilitation design specified the use of 0.8 m (2.5 ft) diameter, standard dimension ratio (SDR)-11 solid-walled HDPE manholes to replace the damaged manholes. The new manholes were connected to the existing LCS pipe network. Prior to installation of the new manholes, arrangements were made to collect samples of LCS drainage sand and geofabric surrounding the pipe.

The original plan to collect LCS drainage sand samples called for the use of a vertical coring device. However, the wet nature of the material and the sloughing-off of the material into the excavated areas made this option unfeasible. Two alternative sampling techniques for the drainage sand were utilized. One technique involved collecting disturbed drainage sand material from the bottom of the excavation areas and storing in 2-liter HDPE containers. Attempts were made to collect any material believed to be representative of the LCS drainage sand. The second method involved pushing a coring device horizontally along side the LCS pipe into the landfill, and then excavating the core. The coring device was made of PVC, 0.9 m in length and a 7.6 cm diameter (3 ft in length and 3 in. in diameter). This method was believed to collect the most undisturbed sample possible. The environment and the nature of the construction allowed only a limited window of opportunity for sample collection. Therefore, it was not possible to take core samples in all circumstances. Sand samples from the original borrow pit were taken and analyzed for comparison to the LCS drainage sand.

Geotextile fabric was collected by cutting sections from the LCS pipes and storing these coupons in plastic containers. All samples of drainage sand and fabric were transported from the field at the end of each day and stored in a cold room at 4° C until analysis.

3.1.3 Sample Analysis

Characterization of the LCS materials included permeability, grain size distribution, volatile solids, and metals analysis for common constituents associated with chemical precipitation under landfill conditions.

3.1.4 Physical Characteristics

Found in this section is a description of each testing procedure utilized in this field study to determine the physical characteristics of the drainage sand and the geotextile sock

3.1.4.1 Soil Permeability

Clogging of a drainage material may be characterized by measuring the permeability of the soil and geotextile. From the perspective of LCS clogging, it is desirable to analyze samples in the exact condition as found in the field. Collection of such samples in the field was not found to be possible for this project. Typical permeability tests for sands and gravels involve reconstituting an air-dried soil sample in a permeameter and conducting a constant head permeability test. The actual mixing and air drying of such a sample may have an impact on the permeability by changing speciation of chemical precipitates and drying bacterial mass.

To minimize the impact of drying, the testing procedures employed here deviated from the standard method by testing the drainage sand without air drying prior to loading the permeameter. The goal of this method was to maintain as much as possible the biological and chemical characteristics of the samples during the testing procedures. It should be noted that the time required by ASTM D-2434 for de-airing and saturation of the sample was doubled to ensure equivalent flow through the soil columns. Hydraulic conductivity tests were performed utilizing constant heads of 77, 62, and 37 cm and measuring the liquid flow through the column was measured. For comparison of the standard and modified test methods, additional samples were analyzed using the conventional ASTM D-2434 testing procedure. A comparison of the results indicated that modified method was applicable.

3.1.4.2 Geotextile Permittivity

The geofabrics were removed from the plastic containers and placed in a testing apparatus which conformed to the design specifications outlined in ASTM D-4491. A constant head was applied and the flow of liquid passing through the drainage material was measured. The samples of the geofabric were then “cleaned” by washing with an acidic solution followed by deionized water in an effort to restore the original characteristics of the material. The “cleaned” samples were then tested under analogous conditions.

3.1.4.3 Grain Size Distribution

Further characterization of the soil drainage layer included grain-size distribution analysis. Approximately 500 grams of sample were used to perform the analysis using a Lesson RX-86 shaker table and stainless steel sieves. Grain-size distributions for all drainage sand samples were compared using uniformity coefficients. The uniform coefficient (C_u) is a ratio of the grain diameter corresponding to 60% passing to the grain diameter corresponding to 10% passing (by weight). A C_u value of 1 indicates a poor distribution of grain sizes, while a C_u value greater than 15 indicates a well graded soil (Holtz and Kovacs, 1981).

3.1.5 Chemical Characteristics of Drainage Sand

Found in this section is a description of each testing procedure utilized in this field study to determine the chemical l characteristics of the drainage sand.

3.1.5.1 Volatile Solids

Volatile solids analysis was performed on all soil samples. This test provides an approximation of the biological fraction of the solid sample by mass. Oven dried samples were mixed in a plastic container, weighed, and then placed in a muffle furnace at 550 ^{o}C to determine the volatile content. Similar volatile solids analysis was performed on all sieve fractions. As a result of small pieces of organic materials (plant roots) found in the LCS sand and borrow source, the volatile solids of the sand fraction passing a 0.85-mm sieve was used to characterize the sand.

3.1.5.2 Metals Analysis

An acid digestion procedure was used to prepare soil samples for metals analysis by flame atomic absorption spectroscopy. Through this aggressive eight-hour digestion process, the metals contained within one to two grams of sample are dissolved into solution. The solution was then filtered and analyzed on a Perkin Elmer 5100S Atomic Absorption Spectrophotometer for calcium, iron, magnesium, and potassium.

3.2 Results

3.2.1 Physical Characteristics of Drainage Sand

Results for the physical characterization of the sand drainage layer, including constant head hydraulic conductivity and grain size distribution, are presented in this section. Borrow samples are representative of the clean sand prior to exposure to landfill conditions.

3.2.1.1 Soil Permeability

The average hydraulic conductivity of the original borrow sand was determined to be 1.85 x 10^{-2} cm/sec. The hydraulic conductivity of all sand samples ranged from 9.72 x 10^{-3} to 1.83 x 10^{-2} cm/sec. Thus, the reduction in permeability of the sand drainage layer varied from 1% to 47%. However, the 47% reduction occurred in only one sample, and on average, the permeability of the drainage sand was 1.23 x 10^{-2} cm/sec. Thus, the average reduction in permeability was 33%.

3.2.1.2 Grain-size Distribution

Grain size distribution tests found uniformity coefficients to be close to one for all sand samples. This indicates that the sand drainage samples have poor gradation of particle sizes. The samples generally have a uniform particle size with diameters in the range of 0.1 to 0.3 mm (0.03 to 0.08 in). The soil corresponding to this diameter range is a medium to fine sand. Sand of this nature is highly permeable (hydraulic conductivity range of 1.0 x 10^{-2} to 1x 10^{-3} cm/sec) due to minimal clogging of pore spaces by silts and clays.

It was observed in the field that the borrow sand contained a negligible fraction of fine particles. Therefore, clogging of the sand due to particle intrusion into pore spaces was expected to be insignificant. Further inspection of the air-dried soil samples after sieve analysis revealed a minimal percent fines by mass. As a result, minimal clogging of the LCS sand was expected due to particulates. The results of permeability analysis confirm that the soil samples behave as medium to fine sands.

3.2.2 Chemical Characteristics of Drainage Sand

Results for the chemical characterization of the sand drainage layer, including volatile solids and metals analysis are presented below.

3.2.2.1 Volatile Solids

The drainage sand generally had a higher volatile solids content compared to the borrow sources. The average percent volatile solids for the borrow sand and drainage sand was 0.2% and 0.4%. Microbial growth on these particles and chemical precipitation in the media provides the organics that are volatilized. As shown in previous laboratory studies, the formation of a biological/chemical precipitate barrier layer on top of the drainage media inhibits flow through the system. Sampling techniques and the nature of the waste-LCS interface did not allow for sampling of the upper layer of the drainage sand and thus an overlying barrier layer to the LCS could not be tested. However, the results from the volatile solids analysis indicate minimal biological growth within the sand drainage layer.

3.2.2.2 Metals Analysis

The major contributing constituents for chemical precipitation in leachate collection systems (Ca, Fe, Mg, K) were analyzed. Precipitation of calcium carbonate and ferrous salts due to sulfate-reducing bacteria has been shown to clog drainage media (Rohde and Gribb 1990, Rittman et al. 1996).

The average concentrations for Ca, Fe, Mg, and K in the borrow sand was 10.9, 142.7, 4.1, and 29.2 mg/kg, respectively. The LCS sand had average concentrations of 881.7 mg/kg for calcium,458.4 mg/kg for iron, 101.9 mg/kg for magnesium, and 96.0 mg/kg for potassium.

3.2.3 Geotextile Permittivity

Initial inspection of the geotextile upon removal from the LCS pipes found small amounts of black slime and sand embedded in the woven material. However, permittivity testing of the fabric indicates that the reduction of flow after six years of exposure to landfill conditions is negligible. Relative to the cleaned samples, the geotextile permittivity had a minimum reduction of 2% and a maximum reduction of 75%. The average reduction was determined to be from 6.4 sec^{-1} to 3.3 sec^{-1}. Although there was a high level of reduction found in many of the samples, the maximum reduction corresponds to a permittivity value of 1.6 sec^{-1}. Thus, the geotextile was still capable of transmitting high flowrates, and was not a factor in clogging of the LCS.

3.3 Impact on LCS Performance

As previously discussed, the permeability of the leachate collection system is a primary factor in determining the collection efficiency. The purpose of this study was to examine the conditions of drainage media collected from an operating landfill to assess the degree of clogging (reduction in permeability and permittivity). From the analysis of drainage sand and geotextile samples it was determined that both displayed some degree of clogging. The following is quantitative comparison of the initial calculated head on the liner and the calculated head on the liner due to clogging of the system. The Modified Giroud Equation (1995) was utilized to estimate the head on the liner:

Because the drainage sand has a lower average permeability (k) relative to the permittivity of the geotextile, it was the limiting factor in the permeability of the drainage system. The initial and "clogged" values were 1.85 x 10^{-2} and 1.23 x 10^{-2} cm/sec, respectfully. The length of one side of the collection area (L) was 45.7 m (150 ft). The slope of the collection area (α) was 1% and the average impingement rate (e) was 0.6 L/m^2-day (666. 7 gal/acre-day). The calculated head on the liner for initial LCS conditions was 7.4 cm (2. 9 in) and 10.6 cm (4.2 in) after seven years of exposure to landfill conditions.

3.4 Conclusions

The analysis of the leachate collection system indicates that clogging mechanisms played a minor role in the reduction of flow. The collapse of the sectional manholes and the intrusion of sand and waste into the pipe network were the overriding cause for LCS failure. It should be emphasized that this site was not chosen based on possible clogging mechanisms, but rather the unique opportunity to sample components of a LCS from an active landfill. The Modified Giroud Equation estimated that clogging mechanisms caused a head increase of 3.2 cm (1.3 in) on the liner; however, the resulting head on the liner, 10.7 cm, is well within the 30 cm requirement.

4. RECOMMENDATIONS

4.1 LCS Clogging Field Study Design

The most direct method to assess clogging of Florida LCSs would be to conduct a field study of LCS performance. This field study should consist of several test cells located through out the state of Florida. Site selection should be based on representing the full range of climates which can be anticipated in Florida. These test cells should be constructed with identical leachate collection systems. The leachate collection systems should contain a dense array of pressure transducers for the measurement of leachate head within the liner. Particular care should be made to ensure readings on both sides of material interfaces. In addition to monitoring leachate head, precipitation data and leachate production rates should be monitored. It will also be important to determine through laboratory testing the amount and size distribution of fines released by both the materials in the LCS and the placed waste. Monitoring the particles produced with the leachate outflow will then provide the information required to conduct a phenomenological, mass balance approach to the entrapment of fines within the LCS. This information will lead fairly directly to the estimation of permeability decreases which could be expected from particle transport and deposition. Permeability decreases in excess of this estimated could then be attributed to biological growths and chemical precipitates.

1. INTRODUCTION

Groundwater has been shown to be the primary contaminant release route at problematic landfills. The leachate collection system (LCS) is the ultimate barrier between the environment and landfill leachate and is thus subject to intense scrutiny during both the design and installation phases. The Florida Department of Environmental Protection (FDEP) requires a bottom liner for all municipal solid waste (MSW) landfills in Florida. The FDEP, in compliance with RCRA-subtitle D regulations, has variable head requirements ranging from one inch to one foot depending on the design of the liner system. These maximum heads are design standards and it is presumed that the performance of a LCS designed based on these heads will not violate the FDEP or RCRA regulations.

The drainage system, located above the liner, is perhaps the most critical element of the collection system, and generally consists of highly permeable natural materials such as sand or gravel or a geosynthetic net. The drain is often protected by a natural soil or a geosynthetic filter in order to minimize clogging. Research at several northeastern landfills has shown that the ability of the LCS to remove leachate from the landfill may significantly deteriorate over time due to clogging of the drainage materials used in the LCS. Koerner and Koerner (1991) concluded that the filter should be the focus of concern in the leachate collection system because of a reduction in permeability over time. Filter clogging results from sedimentation, biological growth, chemical precipitation and/or biochemical precipitation, and is quite difficult to control. Clogging is most often experienced during the acidogenic period when organic substrates and precipitating metals such as calcium, magnesium, iron, and manganese are most highly concentrated in the leachate. Florida’s hot, humid climate may provide more optimum conditions for biological growth in the LCS resulting in a greater potential for LCS failure.

LCS clogging can lead to build up of excess head on the liner which may increase the risk of leakage through the liner. With leachate buildup, the possibility of side seeps and stormwater contamination increases. In addition, saturated conditions within the landfill can lead to instability issues.

Two distinct efforts were required to assess the potential for clogging of LCSs at Florida Landfills. A University of Florida effort examined the extent of clogging that had occurred in an MSW landfill leachate collection system that had been in operation for six years. Research conducted at the University of Central Florida compared LCS designs and safety factors at existing Florida landfills to recommended design practices and safety factors.

2. LITERATURE REVIEW

2.1 Leachate Collection System Design

2.1.1 Design Equations and Techniques

The LCS is the ultimate barrier between the environment and landfill leachate and is thus subject to intense scrutiny during both the design and installation phases. There are two basic liner types currently in use, the composite (Figure 2.1) and double-composite liner.

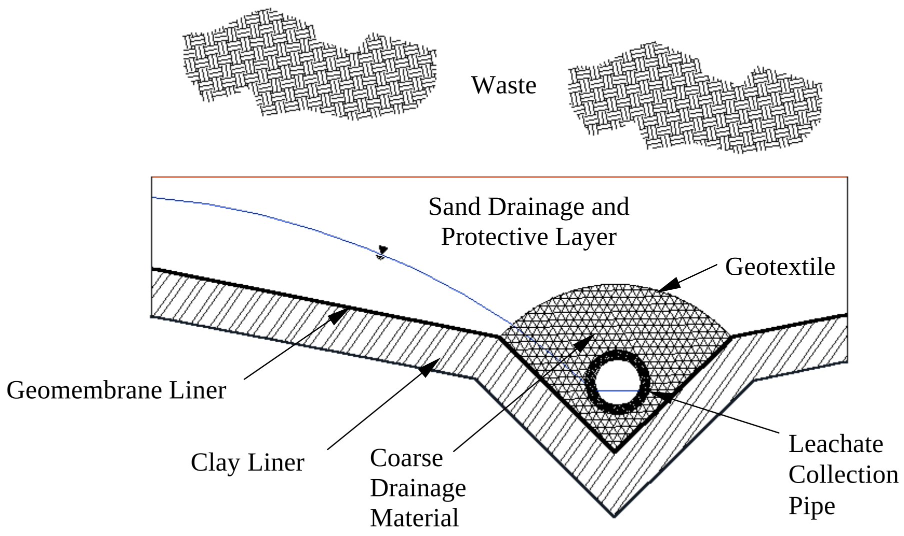

Figure 2.1. Schematic diagram of a composite liner system.

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

2.1.1.3 Design Equations

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

Several EPA guidance documents have presented Equation 1 (US EPA, 1989) for use in predicting the maximum saturated depth over the liner.

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

where:

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

McEnroe (1993) used the extended Dupuit assumptions for unconfined flow to develop equations (2a, b, and c) for the steady-state saturated depth over a liner.

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

for R<1/4

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

for R=1/4

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

for R>1/4

where:

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

McEnroe developed a dimensionless form of the equation recommended by the US EPA, Equation 1 above. This dimensionless equation has the form shown below in Equation 3. McEnroe compared Equation 3 to Equation 2 and found that for values of R less than one the EPA equation significantly over-predicted Y_{max}.

$$Y_{max} = R^{1/2}\left[1 - \frac{(1+R)^{1/2} - 1}{R}\right] \qquad (3)$$

Where all variables were previously defined.

Giroud proposed analytical methods to calculate the thickness of head on the liner under steady-state and unsteady-state conditions (1992). In 1985, Giroud introduced an empirical equation comparable to the McEnroe and Moore equations. The modified equation (Equation 4) presented here introduces a corrective coefficient (j) to achieve values comparable to numerical solutions.

$$\frac{h_{max}}{L} = \left(\frac{\sqrt{1+4\lambda} - 1}{2} \times \frac{\tan\alpha}{\cos\alpha}\right) \times j \qquad (4)$$

$$j = 1 - .12\exp\left\{-\left[\log\left(\frac{8\lambda}{5}\right)^{5/8}\right]^{2}\right\} \qquad (5)$$

$$\lambda = \frac{q_i}{k \cdot \tan^{2}\alpha} \qquad (6)$$

h_{max} = maximum head on the liner, L
λ = dimensionless variable defined in equation 6
L = horizontal drainage distance, L
α = inclination of liner from horizontal, degrees
k = hydraulic conductivity of the drainage layer, LT^{-1}
q_i = impingement rate, LT^{-1}

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

Equation 7 has been recommended for use in determining the spacing between collection pipes in a LCS using a geonet between the liner and gravel (US EPA, 1989).

$$\theta_{\text{reqd}} = \frac{qL^2}{4h_{\text{max}} + 2L\sin\alpha} \tag{7}$$

Where:

θ_{reqd} = transmissivity of geonet, L^2T^{-1}
L = distance between collection pipes, L
h_{max} = maximum head on liner, L
q = infiltration from a 25 year 24 hour storm, LT^{-1}
α = slope of drainage system, degrees

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

Leachate collection systems are commonly constructed with layered materials as shown in Figure 1. The intent of this design is to use fine-grained materials on top of coarser grained materials in order to filter out materials that may clog lower layers or the drain pipes. Yeh et al. (1994) investigated wicking effects within the drainage layers of the collection system. The wicking effect is a result of capillary forces and may enhance spreading while impeding vertical moisture flow. This effect is due to the difference in unsaturated flow characteristics at the interface between the two drainage media. Capillary forces may make it more energy efficient for the leachate to spread horizontally in the fine-grained media rather than to enter the gravel layer of the collection system. This effect is most noticeable for low flow, dry conditions with a fine-grained soil overlaying coarse media. Once a breakpoint saturation is reached in the fine-grained media, moisture will enter the coarse-grained material. The wicking effect may result in ponding above the fine-grained material. A suggested remedy was to use a three-media collection system consisting of fine-, medium-, and coarse-grained materials (top to bottom). This would decrease the interface difference in characteristics and thus decrease the wicking effect.

Oweis and Biswas (1993) examined the effect of percolation rate on the leachate mound. The study consisted of the development of direct equations which were compared to results obtained using the USGS MODFLOW software package. The equations developed can be used to predict changes in the leachate mound as a result of changes in the percolation rate. Results indicated that the leachate mound was very sensitive to changes in the percolation rate and that effective capping decreases the mounding of leachate within the fill.

Koerner and Koerner (1995) discussed clogging of the LCS components, particularly the geotextile filters and fine-grained media commonly used in the LCS drainage layers. A series of vertical flow studies were conducted using 100-mm rigid wall permeameters filled with various combinations of drainage materials underneath MSW. They found that when MSW was placed directly on top of the gravel in the drainage system (no filter material was used) leachate would buildup in the waste layer but was removed quickly once it reached the gravel media. The permeability of systems which used a combination of gravel and a filter material declined much more rapidly than did the permeability of the gravel only drainage systems. A small amount of fine particles was observed to migrate through the gravel-only system over time. They also discussed the possibility that carbonate present in the coarse media may react with the leachate and cause agglomeration of the media. The limestone used in this study had a carbonate content of 5% and did not exhibit any agglomeration. They concluded that a decrease in the permeability of the drainage media should be anticipated when designing the LCS.

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

Boschuk, 1995 reported that in one failed LCS, a designed and installed 2.5% slope had changed to a negative 3% slope as the result of settling and compression of the subgrade.

2.1.2 Safety Factors

The direct application of safety factors to the clogging of soils and geotextiles is a fairly new concept for LCS design as well as other drainage and soil erosion prevention systems. The use of safety factors for the LCS scenario is complicated by the many potential clogging mechanisms, particulate entrapment, biological growth, and precipitate formation, as well as the variety of materials and configurations used. The Solid Waste Disposal Facility Criteria Technical Manual (US EPA, 1993) mentions the use of appropriate safety factors and performance design ratios in its discussion of the utilization of geonets in LCSs but does not specify what appropriate values are or how to calculate them.

Koerner et al. (1994) present the only quantitative safety factor based design equations for landfill LCS. They suggest the use of Equation 5 for the selection of the design geotextile filter permeability but indicate that it may also be applied to the selection of granular drainage media.

$$FS = \frac{K_{allow}}{K_{reqd} \cdot DCF} \tag{5}$$

where:

FS = factor of safety against long term clogging
K_{design} = allowable design permeability for long term system performance, L/T
K_{reqd} = minimum permeability required for acceptable system performance, L/T

DCF = drain correction factor accounting for LCS configuration

The parameters K_{reqd} and K_{allow} represent the minimum permeability required to prevent the buildup of excessive hydrostatic pressures and the design permeability used to anticipate the long-term deterioration in permeability which can be expected. Therefore, K_{allow} will always be greater than K_{reqd}. The drain correction factor in Equation 5 is used to account for the configuration of the LCS and is calculated as the total cell area divided by the available filter flow area. Table 1 contains information on the value of the DCF for some common LCS configurations. Based on the effect of the DCF on the factor of safety in Equation 5, Koerner and Koerner recommend placement of a geotextile over the entire landfill footprint (DCF = 1) rather than wrapping the collection pipe (DCF = 7,500 to 24,000). They also suggest that wastes with low concentrations of fines should be placed in the first layer on top of the filter in an effort to limit the particle loading on the geotextile filter. In his presentation at the Seminar on Landfill Bioreactor Design and Operation (Wilmington, DE, March 23-24, 1995) George Koerner indicated that appropriate safety factors for drainage systems are not 2 or 3 but rather, at least 10 to account for the long-term permeability decreases which can be expected.

Table 2.1. Values of the drainage correction factor values for various LCS configurations.

LCS Configuration	DCF
Geotextile placed over entire cell footprint	1
Geotextile wrapped around gravel drain (burrito)	10 to 40
Geotextile wrapped around a slotted, corrugated pipe (socked)	60 to 260
Geotextile wrapped around a smooth, perforated pipe (socked)	7,500 to 24,000

Giroud, 1996, makes the following qualitative recommendations for filter selection to minimize the risk of clogging:

- sand filters and nonwoven geotextiles filters should not be used,
- if a filter is used, a monofilament woven geotextile (perhaps treated with a biocide) with a minimum filtration opening size of 0.5 mm and a minimum relative area of 30 percent should be selected, and
- the drainage medium should be an open-graded material, such as gravel, designed to accommodate particle and organic matter passing through the filter.

2.2 Landfill Leachate Collection System Clogging

2.2.1 Simulated LCS Studies

Laboratory studies provide valuable information without the difficulties of on site excavations. These studies allow the investigators to study specific clogging mechanisms under predetermined conditions.

2.2.1.4 Aerobic and Anaerobic Conditions

Research involving clogging of sand/geotextile and geotextile drainage systems was performed at the Geotextile Research Institute at Drexel University (Koerner and Koerner, 1987). All testing procedures utilized six types of geotextiles and leachate from six different landfills. This study consisted of two phases. Phase I involved permeability testing of sand/geotextile composite systems under aerobic conditions as well as permeability testing of geotextiles incubated in anaerobic conditions. Falling head permeability tests were performed on the soil/geotextile systems. The test involved vertical flow of leachate through a sand and geotextile column, followed by horizontal flow through a geonet drain. Flow rate reduction varied from 10% to 100% (no flow detected) after 12 months of exposure to the leachate. The varying reduction was directly associated with the strength of specific leachates and the type of geotextile being tested.

Anaerobic conditions were achieved by immersing geotextile samples in sealed 55-gallon drums filled with leachate. Constant head permittivity and radial transmissivity tests were performed on all samples. These results were then averaged together to get flow rates through the geotextile samples. Flow rate reduction ranged from 5% to 20% for all samples. Similar to aerobic conditions, stronger leachate was associated with larger reductions in flow rates.

Phase II of the project incorporated a new apparatus for sand/geotextile and geotextile permeability testing as well as remediation techniques for the samples. This portion of the study was the model for American Society of Testing and Materials (ASTM) standard method D-1987: *Biological Clogging of Geotextile or Soil/Geotextile Filters*. The new apparatus was an eight-inch permeameter that was adaptable to falling and constant head permeability tests. Flow reduction varied from 10% to 100% (below detection limits) for all samples. As expected, soil/geotextile composite systems experienced a greater reduction in flow in comparison to the geotextiles alone. On average, the soil/geotextile filters had an additional 11% reduction. Remediation techniques, such as backflushing and vacuum extraction, explored in this study had minimal impact on the long-term restoration of flow for both scenarios.

2.2.1.5 Anaerobic Conditions

A similar study emphasized biological and particulate clogging of sand/geotextile drainage systems under anaerobic conditions (Rohde and Gribb, 1990). A total of four permeameters were constructed with the ability to determine head loss along the soil column and across the geotextile. Leachate from a local municipal solid waste landfill was used in the constant head permeability tests. Two biological inhibitors, sodium molybdate and mercuric chloride, were added to two columns as a means of differentiating biological clogging from other mechanisms. Flow reductions in all permeameters ranged from 92% to 97%. The governing factor affecting the permeability of the columns was the accumulation of black particulates in the upper drainage layer. The particulates were determined to be ferrous sulfide salts resulting from microbial sulfate reduction. The first 7.0 cm of sand accounted for 90% of the reduction of flow through the permeameter. As a result, clogging mechanisms had an insignificant effect on the hydraulic properties of the geotextile.

2.2.1.6 Chemical Precipitation

A study was performed to evaluate clogging of drainage media due to calcium carbonate precipitation , which in turn was thought to be a function of microbial oxidation of COD to inorganic carbon (Rittmann et al., 1996). Previous studies in this field led investigators to believe that the rate of clogging of LCS is controlled by changes in leachate chemistry, primarily calcium concentrations and chemical oxygen demand (COD) (Rowe et. al., 1995). To analyze the effects of leachate chemistry on LCS performance, fresh leachate samples from the Keele Valley Landfill were utilized as the influent for the laboratory simulators. These reactors were rectangular boxes containing 0.3 m of clear stone (drainage layer) overlain by 0.15 m of composted refuse. The leachate samples and the effluent were analyzed in order to determine the change in leachate chemistry. The results for a representative set of samples are presented in Table 2.2.

Table 2.2. Changes in Leachate Quality Parameters

Parameter	Leachate	Effluent	Change
Temperature, ^{o}C	28	28	0
pH	7.05	8.5	+1.45
COD, mg/l	12,000	2,000	-10,000
VFA mg/l as HA	7,800	1,200	-6,600
T-ALK, mg/l as $CaCO_3$	8,100	7,400	-700
B-ALK, mg/l as $CaCO_3$	2,600	6,500	+3,900
BASE, mg/l as $CaCO_3$	9,100	7,500	-1,600
SO_4^{2-}, mg S/l	0	0	0
$C_{T,CO3}$, mole/l	5.2E-02	1.3E-01	+7.8E-02
CO_3^{2-}, mole/l	7.6E-05	4.5E-03	4.424E-05
Equil. Ca^{2+}, mg/l*	19	0.3	-18.7
Ca^{2+}, mg/l	800	250	-550
Ca^{2+}-BASE, mg/l as $CaCO_3$	2,000	625	-1,550
S.I.	1.3	2.4	+1.1
$H_2CO_3*_{,}$ moles/l	7.9E-03	6.3E-04	7.6E-05
Equil. $P_{CO2,}$ atm**	0.23	0.02	-0.21

* Assuming solubility-product equilibrium with CO_3^{2-}

** Assuming Henry's Law Equilibrium with H_2CO_3*

The results suggested that COD removal accelerated the precipitation of calcium carbonate (0.058 mg Ca^{2+}/mg COD). Calcium carbonate was determined to be the primary component of the clogging material. Rittmann et. al (1996) further indicates that the loss of COD in the form of acetic acid and conversion into CO_2 facilitates the formation of H_2CO_3. The result is an increase in pH and carbonate concentration, and ultimately an increase in calcium carbonate precipitate.

2.2.2 Field Studies of LCS

Although laboratory simulations are adequate for studying clogging mechanisms, they may not accurately represent conditions within a landfill. Investigations involving excavated drainage material are vital because the results indicate actual environmental effects on the collection efficiency.

2.2.2.7 Multiple Site Study

The Geosynthetic Research Institute at Drexel University used field studies of four different sites to validate a proposed factor of safety equation for design specifications of geotextiles used in leachate collections systems (Koerner et al. 1993). Cleaned samples were used to estimate initial values for the material. Table 2.4 outlines critical characteristics of the leachate in accordance with potential clogging mechanisms.

TABLE 2.4. Comparison of Selected Leachate Characteristics

Site Number	Landfill Type	pH	COD (mg/l)	Total Solids (mg/l)	BOD_5 (mg/l)
1	Municipal	6.9	31,000	28,000	27,000
2	Municipal	7.5	10,000	3,000	7,500
3	Industrial	9.9	3,000	12,000	1,000
4	Municipal	6.1	24,000	9,000	11,000

The first site, built in 1981, was a low elevation drainage trench consisting of 4-inch perforated PVC pipe wrapped ("socked") with a nonwoven heat-bonded geotextile embedded in 24 inches of poorly graded crushed stone. Upon excavation, it was noted that the void spaces of the stone were filled with fines and biomass, thus agglomerating to form a "biorock". The geotextile and the crushed rock had flow reductions approaching 100%. The second site was located at the same landfill, but was installed five years later to intercept side wall leachate seeps created by clogging at the previous site. The collection system consisted of a 4-inch perforated high-density polyethylene (HDPE) pipe wrapped in rounded quartz gravel enveloped by a nonwoven monofilament geotextile. Testing of the geotextile indicated a "nominal" decrease in flow (0.9 sec^{-1} to 0.033sec^{-1}).

The third site was a small industrial landfill constructed in 1990. Although the design of the collection system included a leak detection system (LDS), only the primary collection system was investigated. The system was composed of geotextiles above and below a pea gravel drainage media. A 4-inch perforated PVC pipe within the gravel was overlain by the bottom geotextile to form "socked" pipe. Due to nonuniformity of the clogging in the collected sample, the geotextile sock was exposed to simulated field conditions for six months and then analyzed. The results, found in Table 2.5, indicated that the upper geotextile displayed a two-order of magnitude decrease in permeability while the geotextile sock experienced a five-order of magnitude decrease in permeability.

TABLE 2.5. Permittivity Test Results for Geotextiles from Site #3

Number	Description	Permittivity (sec^{-1})	Permeability* (cm/sec)
1	Cleaned Geotextile	1.8	0.5
2	Upper Geotextile	3.14E-02	8.6E-03
3	Geotextile sock**	1.57E-05	4.3E-06

*Permeability values were calculated based on a measured geotextile thickness of 2.74 mm
**The geotextile used was a site specific geotextile conditioned with a fine slurried waste

The final site was different from the previous field locations in that the material tested was a needle-punched nonwoven geotextile wrapped around a well casing used for methane gas extraction. Samples were collected at depths of 10, 25, and 50 ft. The extent to which the geotextile was fouled by organic matter and fine sediments increased with depth. Compared to the cleaned sample, the average reduction in permeability was four-orders of magnitude (Table 2.6).

TABLE 2.6. Permittivity Test Results for Geotextiles from Site #4

Description	Permittivity (sec^{-1})	Permeability* (cm/sec)
Washed Geotextile	1.1	2.3E-01
Geotextile (10 ft down)	1.7E-02	3.8E-03
Geotextile (25 ft down)	7.3E-05	1.6E-05
Geotextile (50 ft down)	3.4E-04	7.5E-05

2.2.2.8 Fresh Kills Landfill Study

A field study was completed at the Fresh Kills Landfill, New York (Corcoran and Bhatia, 1990). The study involved a simulation of a LCS that was designed for the landfill and analysis of the geotextile to determine its effectiveness as a filter for the overlying protective soil. The information acquired was then used to reevaluate the original LCS design. The project called for a collection system with a slotted pipe overlain with gravel. A non-woven geotextile was then wrapped around the gravel. After 4.5 years, the LCS was excavated and sampled. Using a constant head permeameter, it was determined that only a slight reduction in permittivity occurred when exposed to the landfill environment. The reduction in permittivity compared to the initial condition was from 0.8 sec^{-1} to 0.06sec^{-1}. The decline in performance was attributed to fine grained soil particles settling within the geotextile filter. Photographs taken through a microscope showed that the soil intrusion decreased with depth into the filter. As a result, it was determined that the geotextile would be satisfactory in constructing the LCS at Fresh Kills Landfill.

2.3 Clogging Mechanisms

2.3.1 Particulate Clogging

Clogging of porous media is generally attributed to two main phenomenon, particulate transport and biological growth. Particulate clogging is divided into two categories, straining mechanisms and non-straining mechanisms (Reddi, 1997). The straining mechanism scenario occurs when the suspended particles are of comparable size to the filtration media which results in the formation of a cake on the media or mechanical entrapment in the pore spaces of the media. The non-straining scenario refers to the movement of very small particles where physicochemical forces between the particulates and the media drive transport and removal processes. The non-straining scenario is further divided into three particle behavior categories; interception, sedimentation, and Brownian motion (Figure 2.2).

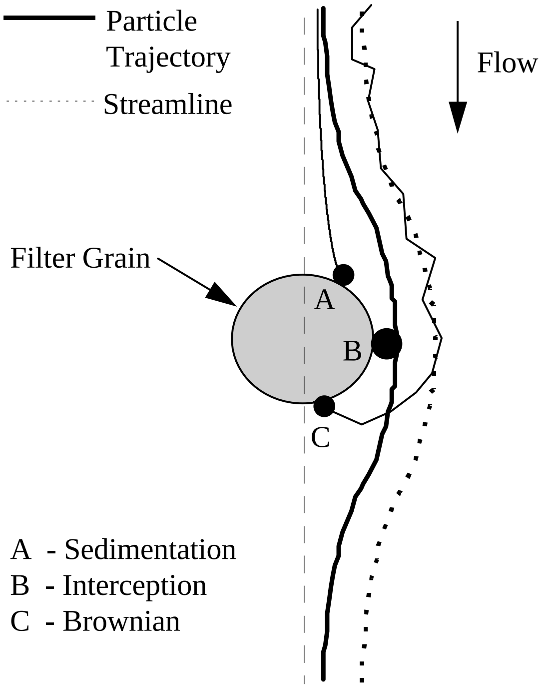

Figure 2.2 Non-straining particulate transport mechanisms.

Interception is the result of the collision of suspended particles with the grains of the filtration media while sedimentation is caused by density differences between the suspended particles and water resulting in particulates deviating from the flow streamlines and settling on the filter grains. Brownian motion describes the movement of micron- and sub-micron particles due to diffusivity. Particle diffusivity is characterized as a stochastic process which may ultimately result in the particle contacting and attaching to filter grains. The evaluation and modeling of particle transport has followed two paths, (1) phenomenological methods which use a filter coefficient to treat particle entrapment as a bulk, mass removal process and (2) particle trajectory methods which evaluate the stability of individual particles as they approach the solid grains of the filter media.

Rao et al. (1991), documented a long-term study of the filtration behavior of soil-geotextile systems. They focused on particulate clogging and the evaluation of the hydraulic gradient ratio test commonly used to assess the permeability of the soil-geotextile system. Geotextile filters are designed to meet two conflicting requirements; soil retention criterion and permeability criterion. The soil retention criterion is directed at preventing the movement of erodible soil particles while the permeability criterion focuses on ensuring free flow of liquid through the filter and minimizing the buildup of excessive hydrostatic pressure. The soil retention criterion is met by comparing the pore size distribution of the geotextile to the particle size distribution of the soil to be retained. The permeability criterion is evaluated by calculating the hydraulic gradient in the soil adjacent the geotextile (Equation 6).

$$k_g > i_s \cdot k_s \qquad (6)$$

where:

k_g = hydraulic conductivity of the geotextile, L/T
i_s = hydraulic gradient in the soil, L/L
k_s = hydraulic conductivity of the soil, L/T

The difficulty encountered when employing Equation 6 is that as erodible soil particles are retained by the geotextile, its permeability will decrease which may alter the validity of the initial calculations. Research has shown that the flow behavior is initially governed by the soil's density and ultimately by the behavior of the soil-geotextile interface. It has also been suggested that soil-geotextile system properties could be altered significantly by clogging, blocking, blinding, and piping over time. The gradient ratio (GR) test is commonly used to measure the clogging potential of a soil-geotextile system. In this test, the ratio of the hydraulic gradient through the geotextile plus 25 mm of soil to that of a vertically stacked 50 mm of soil (see Figure 3) is calculated after 24 hr. A gradient ratio of greater than 3.0 has been shown to signify excessive clogging. A limiting value of 3.0 has been considered acceptable for the evaluation of a soil-geotextile system. The authors conducted longer-term (up to 1000 hr) flow and gradient ratio test on three geotextiles overlain by a combination of Ottawa sand and Dhanauri clay. The particle size distribution of the soil was controlled by varying the percentages of each soil used.

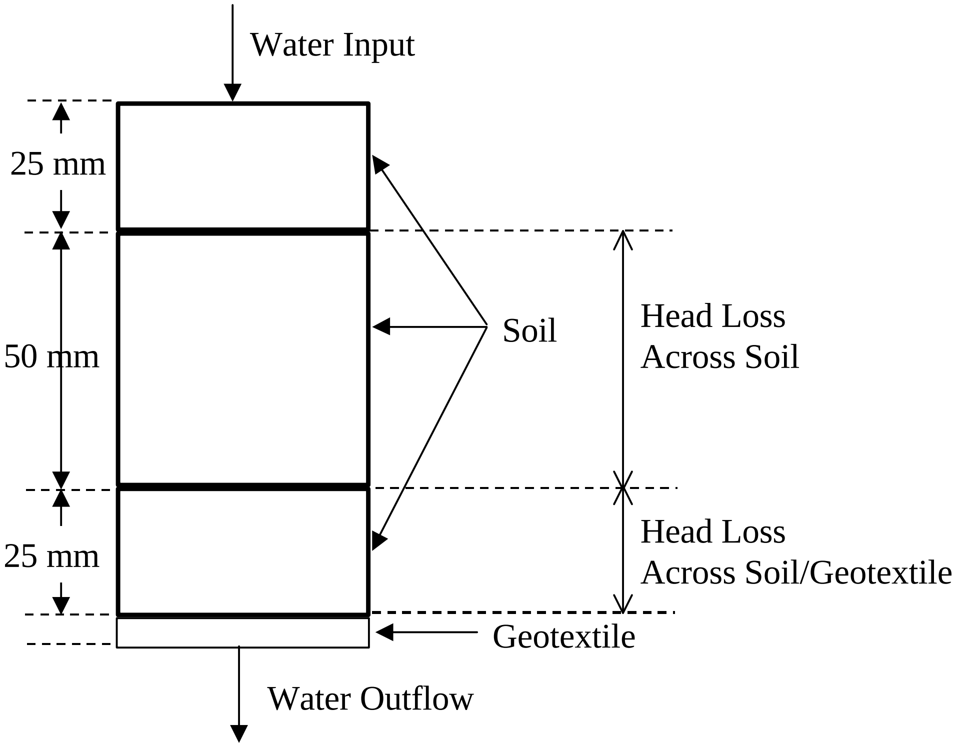

Figure 2.3. Diagram of soil arrangement for the gradient ratio test, Rao et al. (1997).

The test results indicated that the clogging of soil-geotextile system followed three distinct phases:

- soil particles moved towards and deposited on the geotextile decreasing the system permeability,
- at some critical point, the deposited particles were released through the geotextile and the permeability increased, and
- soil particles again become retained on the geotextile forming a cake deposit and the permeability decreases until an equilibrium condition is reached.

The equilibrium condition was not reached until after at least 120 hr of operation and took up to 300 hr in some cases. Ultimately, it was found that the short term GR tests (< 24 hr) did not provide an accurate picture of soil-geotextile system behavior. The use of the long-term gradient ratio test was recommended.

Reddi (1997) presented a discussion of the research approaches and goals of various fields involved in particle transport research. The main fields discussed were wastewater filtration and geotechnical applications which use soil filters to prevent subgrade erosion and protect drainage pipes. Wastewater filtration studies have focused on developing an understanding of the mechanisms involved in straining and non-straining particle transport. Geotechnical studies have focused on straining mechanisms only due to the use of predominantly cohesionless soils in filter media. An interesting difference between the design of wastewater and geotechnical systems is that wastewater systems find particle entrapment highly desirable while geotechnical systems generally focus on limiting particle movement without decreasing permeability. A commonly used filter design criterion cited for geotechnical systems is shown in Equation 7.

$$\frac{D_{15}}{d_{85}} \leq 5 \tag{7}$$

where:

D_{15} = diameter below which 15% of the filter particles lie, L
d_{85} = diameter below which 85% of the background soil particles lie, L

Filter designs based on this criterion have been reported to prevent penetration of the base soil while retaining permeability. Water resources studies of the straining mechanisms involved in sedimentation have also indicated that the ratio of the media particle sizes to the size of the entrained particles accurately characterizes the deposition behavior. Other studies cited indicated that the critical parameter controlling sediment clogging is the ratio of the pore size of the matrix to the size of the entrained particles. Entrained particles with diameters equal to or greater than half the critical pore diameter of the filter media were found to deposit readily and totally clog the columns studied. The limitation of geotechnical clogging studies to addressing only straining mechanisms was cited as a severe research shortcoming. While only one research study definitively demonstrated the inadequacy of considering straining mechanisms alone, the importance of non-straining mechanisms is quickly realized when the transport of fine-particle swelling clays is considered. The entrapment of even a small percentage of these particles over time would result in significant permeability decreases. The primary conclusion of this review was that integration of the research efforts on clogging conducted by the various disciplines is imperative to developing a complete understanding of this phenomenon.

2.3.2 Biological Clogging

The assessment of biological clogging is at least as complex as particulate clogging. Biological clogging is generally defined as either aerobic or anaerobic. Aerobic microbial growths, as would be expected, have been shown to clog porous media more quickly and completely than anaerobic growths. This difference is most likely due to the higher metabolic rates of the aerobic microbial reactions. Most studies which address biological fouling of porous media attribute clogging to the formation of a biological mat. However, work by Vandevivere and Baveye, 1992, which focused on aerobic clogging of sand columns photographed the formation of three-dimensional microbial aggregates within the porous media. These aggregates occupied the open pore spaces within the filter media effectively decreasing the porosity. Some of these bacterial aggregates become entrapped at pore constrictions after being dislodged and entrained in the fluid. In addition to observing the formation of three-dimensional aggregates, the researches found that the solid surfaces of the filter grains were colonized sparsely and irregularly rather than uniformly as would be expected of the development of a bio-film.

Cook et al., 1994 studied infiltration rate changes associated with the irrigation of a highly permeable soil with wastewater effluent. Wastewater effluent was applied intermittently to a 1.5 m wide by 1.5 m long by 2.3 m deep soil monolith for a period of three years. A 50% decrease in permeability occurred over the three year study period. The permeability decrease was attributed to biological clogging due to enhanced microbial activity. Blockages due to entrapment of suspended solids and chemical effects were ruled out as significant mechanisms based on analysis of the wastewater effluent characteristics. A very interesting study result was obtained after an eight month lapse in effluent application. It was assumed that the lapse in application would result in higher infiltration rates due to bacterial die-off however, the lapse in application resulted in the bacteria changing from active form to a quiescent, encapsulated form which further clogged pores and decreased infiltration rates.

3. FLORIDA LANDFILL DESIGN SURVEY

3.1 Methodology

The goals of this project were met by surveying landfill designers and regulators and by collecting design information on the LCSs in existing Florida landfills. Design engineers were surveyed to collect information on the following:

- the estimation of leachate loading rates,
- design head employed,
- preferred liner system,
- collection pipe spacing,
- type of leachate collection pipe used,
- the slope of the drainage length,
- slope of the leachate collection pipe,
- materials generally used,
- maintenance requirements, and
- safety factors used.

Landfill regulators were contacted to collect information on the following:

- the standard design head required,
- LCS maintenance requirements,
- leachate loading calculation,
- preferred design equations,
- quality control, and
- safety factor requirements.

General design information collected on existing Florida LCSs included

- LCS configuration,
- collection pipe spacing,
- type of leachate collection pipe used,
- the slope of the drainage length,
- the slope of the leachate collection pipe, and
- material specifications for existing Florida LCSs.

This information was gathered by contacting landfill owners directly and reviewing landfill designs on file at the Tampa, Orlando, and Jacksonville FDEP offices.

3.2 Survey Results

A summary of the information provided by FDEP representatives, landfill designers, landfill operators, and inspection of landfill designs on file at FDEP offices is presented below.

3.2.1 Florida DEP Representatives

A leachate head of one foot (30 cm) was considered standard by all of the offices. The estimation of leachate arrival to the LCS, the method used to determine pipe spacing, and the selection of the LCS configuration were considered to be completely up to the discretion of the design engineer. Some representatives preferred the use of the HELP model for determination of leachate loadings and determination of pipe spacing. The use of safety factors in the design of the LCS was an ambiguous issue. Common answers to the question, "Are factors of safety required for any of the LCS components?" were "I don't know, the design engineer decides this." and "Safety factors are recommended but not required." Despite the lack of interest in safety factors, clogging of the LCS components was universally considered to be a concern although the exact clogging mechanisms were disputed. One representative felt that clogging of the LCS was a result of chemical reactions due to paper mill wastes while another representative in a different district suggested that clogging may not be the result of biological activity alone.

The use of specified materials in the construction of the LCS is ensured by a third party QA/QC program as well as by site visits by FDEP officials.

Requirements for maintenance (back flushing) of the LCS varied significantly among the districts. Two districts called for maintenance only in the event that clogging of the LCS was suspected while others required semi-annual or annual back-flushing of the system. Two representatives indicated that video taping of the LCS pipes was required. Of these two representatives, one required yearly video taping of the LCS pipes while the other required video taping during permit renewals.

3.2.2 Designers

Surveying landfill design firms produced a wealth of information on the general techniques and assumptions used to design LCSs. Designers indicated that the most strongly regulated design variables were the head on the liner and permeability of the clay barrier. They also commented that the design of the pipe system; particularly size, settlement, flexibility, and mechanical strength; was important.

The range and average values of some of the design parameters are presented in Table 3.1. All of the firms employed HDPE liners in the LCS. Those designers who specified a thickness all indicated 60 mil. Two of the firms indicated they use double liners exclusively.

The use of perforated leachate collection pipes was specified by all of the firms while 'socking' of the pipe with a geotextile was indicated by only one firm. The preferred drainage materials were a geonet/sand system, river rock, or crushed stone. The filter layer was either a geotextile (usually a non-woven) or a sand layer. The firms were evenly split on the use of geotextiles in the LCS. The firms which employed geotextiles used them as part of the gravel envelope surrounding the collection pipe. One firm indicated that while they preferred to use geotextiles, there were cases where the owner or regulator was strongly opposed to them and they were not used. The use of biocide-treated geotextiles was indicated by only one firm.

Table 3.1. Leachate collection system design parameter values used by design firms.

Parameter	range	Median
Leachate loading rate (gpd/acre)	600 - 1000	750
Maximum leachate head (inches)	9 - 12	11
Collection pipe spacing (feet)	60 - 400	180
Collection pipe diameter (inches)	6 - 8	8
Collection pipe material	PVC or HDPE	HDPE
Collection pipe slope (%)	0.5 - 2	1
Drainage slope	0.2 - 2	1

Of the firms surveyed, only one indicated that no safety factors were used in the design of the LCS. However, of the remaining firms, three applied safety factors only to the design of the leachate collection pipes and not to the drainage materials. The two firms utilizing safety factors in design of the drainage materials, used either the HELP model with a 150% safety factor applied to the head on the liner or Equation 5 (above) proposed by Koerner et al. (1994) with an anticipated permeability loss of two orders of magnitude (i.e., $K_{allow} = 100\ K_{reqd}$). When questioned about past design and installation problems, only two firms indicated troubles with the LCS. In both cases, the mechanical crushing of the LCS pipes was the cause of the LCS failure. Corrugated and PVC pipes were cited by one firm as being particularly susceptible to crushing.

All but one of the designers recommended regular flushing of the LCS pipes. Back-flushing was recommended at least annually. One firm recommended semi-annual back-flushing. The firm which did not recommend regular flushing did specify that the pipes should be cleaned by water jetting when poor system performance was observed. It is interesting to note, that all designers feel that LCS maintenance is important but that regulatory opinions on LCS maintenance varied significantly.

3.2.3 Landfill Designs

The design of the LCS of 25 of the 66 Class I landfills in Florida was analyzed. The design date of the landfills ranged from 1986 to 1997. A considerable increase in the detail and complexity of design was noted as time passed. Twelve of the landfills utilized a double liner system, the remainder utilized a composite liner system. The majority of the landfills evaluated used 60-mil HDPE liners in the LCS. Two of the landfills constructed in the late ‘80s (1986 and 1989) utilized 30-mil PVC liners. One of these landfills utilized the liner only on the side slopes of the LCS. The bottom liner consisted of 1 ft of 10^{-8} cm/s permeability clay over 2 ft of 10-7 cm/s permeability clay. Double liner systems used 60-mil HDPE liners for both the primary LCS and the leak detection system. Table 3.2 contains summary design information for the existing Florida LCSs evaluated.

Table 3.2. Leachate collection design parameters for 25 existing Florida landfills.

Parameter	range	average

Collection pipe spacing (feet)	50 - 596	240
Collection pipe slope (%)	0.17 - 1.5	0.65
Drainage slope (%)	0.4 - 5	2

The majority of the landfills (64%) utilized 8 inch perforated HDPE collection pipes. All but one of the remaining designs used 6 inch perforated HDPE collection pipes. The one remaining landfill constructed in 1986 used a 4 inch perforated PVC collection pipe. The leak detection systems utilized either a 4-inch or a 6-inch perforated HDPE collection pipe. It is important to note that all of the designs evaluated used perforated rather than slotted pipes which are generally felt to be more susceptible to clogging. Also, none of the pipes used were corrugated pipes which were indicated by one designer to be susceptible to mechanical crushing.

All of the designs utilized a drainage envelope around the collection pipe consisting of a high permeability drainage material, usually large rock, wrapped with a geotextile. One of the designs had initially indicated socking the collection pipe but, this was changed prior to approval of the design. The fact that no ‘socked’ collection pipes were found, is encouraging. As was noted in the Koerner et al. study above, socking of the collection pipes results in extremely large drainage correction factors which translates to very low factors of safety. Based on Equation 5, assuming that K_{allow} equals K_{reqd} for the geotextile used and the DCF information presented in Table 1, existing Florida LCSs would have safety factors ranging from 0.1 to 0.025. These safety factors are lower than recommended but are much better than the socked pipe scenario ($FS \cong 10^5$).

Seventy-six percent of the landfill designs reviewed incorporated a geonet-sand drainage layer. A large, coarse material such as river rock or gravel was used as the drainage media in the remaining designs. Material specification requirements on the design plans varied significantly. Most designs provided some material quality information usually a material type and permeability specification (i.e. sand, $K=10^{-3}$ cm/s). Some designs specified materials using AASHTO and FDOT material groups while others simply specified a general material type (i.e. sand, gravel, crushed rock). The use of AASHTO and FDOT material specifications is most likely the best policy to ensure that placed materials are equivalent to the materials required by the designer. Materials in these classifications can be directly purchased and field verification would generally consist of a simple sieve test for particle size distribution. The use of permeability specifications would dictate laboratory testing of the materials used to ensure that the installed and stipulated materials are equivalent.

3.3 Conclusions

The review of landfill regulator and designer surveys as well as discussions during TAG meetings produced the following conclusions and observations.

- Both regulators and designers have expressed concerns over clogging of the LCS components. However, material deterioration has not been addressed in designs in the past.

- HELP model-based LCS designs are driven by the open cell condition where all precipitation is received directly by the LCS.

- Traditional, equation based, designs use a lower than regulated maximum head as a safety factor.

- No designers supported ‘socking’ the leachate collection pipes and no existing LCSs evaluated utilized ‘socked’ pipes.

- The permeability of LCS materials may deteriorate over time, however, the amount of leachate received by the LCS will also decrease over time due to placement of final or intermediate caps.

- Concern was expressed that many designers are not familiar with the use of geotextile filters in LCSs and may be using them improperly. Geotextiles should be employed as material separation devices and not as a drainage material.

- In designs which incorporate geonets, our surveys showed that the effect of overlying materials (sand or geotextiles) on the transmissivity of the geonet was properly accounted for using manufacturer provided design information. However, the deterioration of this material which can be expected was not addressed.

- A geotextile study conducted at the Orange County Landfill in Orlando, Florida indicated that the geotextile with the largest initial open area ultimately had the lowest permeability most likely due to clogging.

- Design equations presume uniformly distributed precipitation which is not the case and presuppose the location of the maximum head. Both of these assumptions underestimate the actual performance of the LCS.

- The verification of LCS material quality during construction is done through visual inspection and testing. However, third party quality control is generally expensive and is not required or regulated.

- Maintenance of the LCS, generally flushing once or twice per year, is recommended by most designers however, regulatory requirements vary significantly and the LCS is usually only serviced once a problem has been identified.

- Sites which practice regular back-flushing of the LCS experience increased leachate flows after the back-flushing operation. Work conducted by Koerner and Koerner, (1990) suggests that this increase is most likely due to clearing of the pipe perforations rather than impacting the LCS materials.

- The assessment of existing Florida landfill LCS designs indicates that in general, Florida landfill LCS are well-designed, state-of-the-art facilities. Evaluation of the LCS configuration demonstrated that an envelope consisting of gravel wrapped in a geotextile was used to protect leachate collection pipes. This configuration results in worst case safety factors ranging from 0.1 to 0.025 depending on the exact site dimensions, much less than the recommended order of magnitude. Safety factors in this range have been demonstrated by Koerner et al. (1994) to be associated with less than optimal long-term leachate collection system performance. However, the situation is not as dire as would be indicated by 'socked' collection pipes.

- These results indicate that there is the potential for failure due to clogging of the geotextiles in Florida LCS. The exact degree to which Florida's unique climate impacts the potential for LCSs failure is impossible to estimate. The mechanisms which cause performance deterioration (particle transport, biological growths, and precipitation) are not well understood at this time and will vary significantly from site to site based not only on the configuration of the LCS but also on the characteristics of the LCS materials, the type of wastes placed, leachate quality, and the leachate loading rates. Until a more complete understanding of these factors is reached, a definitive appraisal is difficult.

4. FIELD STUDY OF AN OPERATING LANDFILL

4.1 Introduction

Presented in this chapter is the field study of an operating landfill located in Putnam County, Florida. Tests were designed to characterize the drainage material of the LCS after six years of exposure to landfill conditions. The results of this analysis will determine whether clogging mechanisms have impacted collection efficiency.

4.2 Background

Although the permeability of drainage media can be measured prior to placement in a landfill, little is known regarding the performance of such LCS components under long-term landfilled conditions. Factors such as biological and particulate clogging often reduce the flow allowed through the collection system as compared to initial design conditions. Laboratory simulations are helpful in understanding these inhibiting factors; however, the testing procedures may not accurately represent actual conditions in a landfill. Although collection and analysis of drainage media samples from operating landfills would be valuable, only rare circumstances allow access to the LCS once waste has been placed in an active cell.

This chapter reports the results of a study conducted at an operating landfill in Florida. LCS drainage media samples were collected from a landfill under excavation and analyzed for possible reduction in permeability. Samples included sand from the protective drainage layer as well as sections of geofabric sock obtained from the perforated collection pipes. The hydraulic conductivity was measured for all sand samples and permittivity was measured for all geofabric samples. In addition, a number of physical and chemical tests were performed on the sand samples to evaluate possible mechanisms of LCS clogging. The goal of this study was to provide information of value to the practicing engineer in the design of solid waste landfills.

4.3 Methodology

This section describes the process the process involved in sample collection. Incorporated into this discussion is a description of the excavation site, rehabilitation methods, and an explanation of sampling techniques.

4.3.1 Site Description

The landfill evaluated in this study was constructed in 1991. A single composite liner consisting of 20 cm of clay and a high density polyethylene HDPE geomembrane was used to line 8.1 ha (20 acres). The leachate collection system consisted of a saw tooth trench system with HDPE collection pipe wrapped (socked) directly with geofabric in the trenches. It should be noted that the practice of wrapping pipe directly with fabric is discouraged in today's landfill designs. The entire landfill bottom was overlain by 0.6 m (2 ft) of clean sand mined on site. Manholes were placed inside the perimeter of waste fill (Figure 4.2). The landfill was originally designed for expansion so that a total of 16 manholes would eventually be constructed. A total of eight were in place at the time of this study.

In 1996, landfill operators noticed that leachate was backing up within the manholes of the leachate collection system. Inspection revealed that sections of the manholes were collapsing and allowing drainage sand, cover soil, and waste into the LCS, thus blocking the pipes. The manholes used in the original construction of the landfill consisted of flexible walled polyethylene (PE) that was added in sections as the waste was deposited. Use of this type of construction is not standard practice in modern landfills. A plan was developed to repair the faulty LCS. The project required the excavation of each manhole down to the liner. Thus, an opportunity was offered to examine the condition of the drainage material in the LCS in the areas surrounding the manholes. Both drainage sand and geofabric were available for collection.

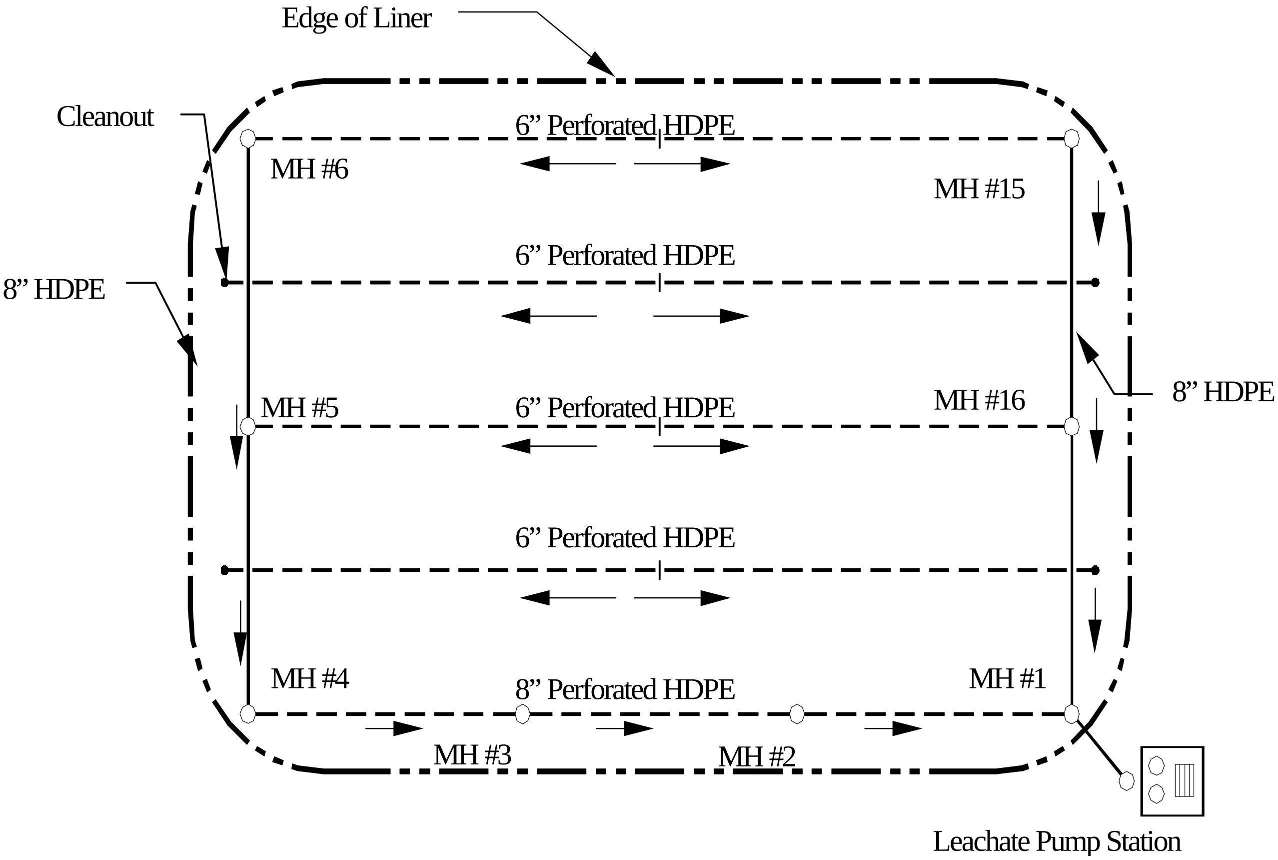

Figure 4.2. Putnam County Landfill LCS Pipe Network

4.3.2 Sample Collection

Excavation of the leachate collection system began in summer 1997. Waste was excavated from the vicinity of the manholes using a track hoe. The depth of waste removed from the surrounding areas of each manhole varied from 2.0 to 7.0 m (6.5 to 23.0 ft). As waste was excavated, individual sections of the manhole were removed until the geomembrane (upper section of the liner system) was reached. Dewatering of the excavated areas inhibited the excavation process. A typical cross-section of the original manholes is presented in Figure 4.3.

The rehabilitation design specified the use of 0.8 m (2.5 ft) diameter, standard dimension ratio (SDR)-11 solid-walled HDPE manholes to replace the damaged manholes. The new manholes were connected to the existing LCS pipe network. Prior to installation of the new manholes, arrangements were made to collect samples of LCS drainage sand and geofabric surrounding the pipe.

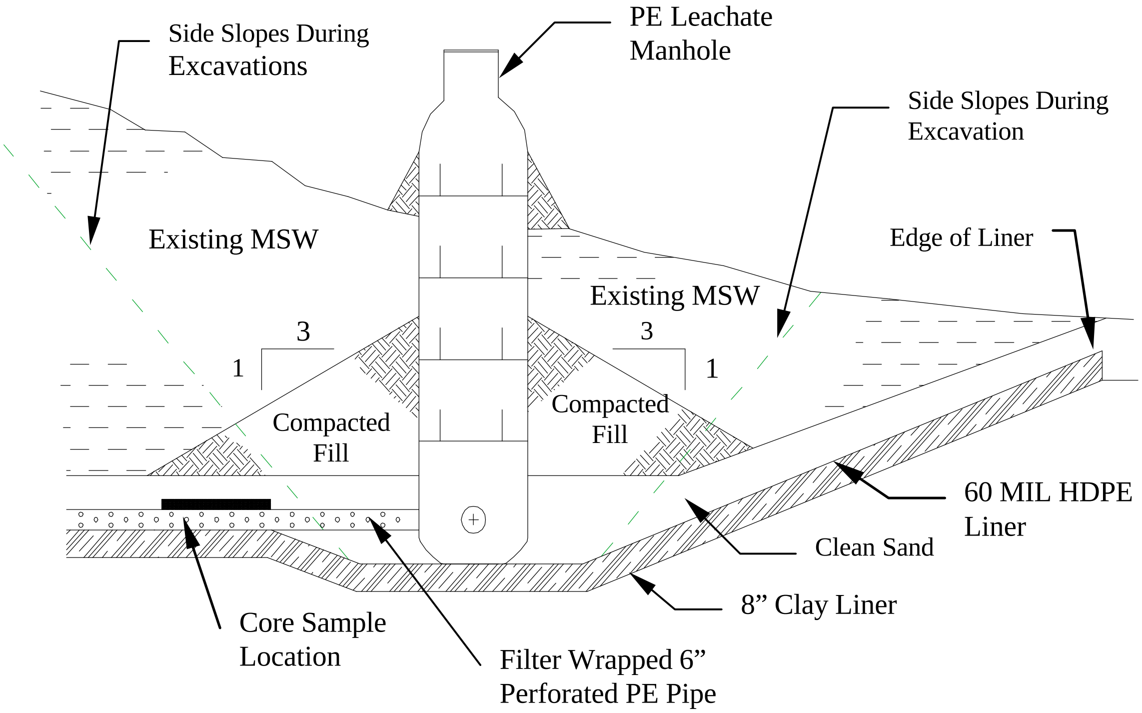

Figure 4.3. Typical Cross Section of Excavated Manholes

The original plan to collect LCS drainage sand samples called for the use of a vertical coring device. However, the wet nature of the material and the sloughing-off of the material into the excavated areas made this option unfeasible. Two alternative sampling techniques for the drainage sand were utilized. One technique involved collecting disturbed drainage sand material from the bottom of the excavation areas and storing in 2-liter HDPE containers. Attempts were made to collect any material believed to be representative of the LCS drainage sand. The second method involved pushing a coring device horizontally along side the LCS pipe into the landfill, and then excavating the core (see Figure 4.3). The coring device was made of polyvinyl chloride (PVC), 0.9 m in length and a 7.6 cm diameter (3 ft in length and 3 in. in diameter). This method was believed to collect the most undisturbed sample possible. The environment and the nature of the construction allowed only a limited window of opportunity for sample collection. Therefore, it was not possible to take core samples in all circumstances. The number and types of samples collected are presented in Table 4.1. Sand samples from the original borrow pit were taken and analyzed for comparison to the LCS drainage sand.

Table 4.1. Collected Samples

Manhole	Horizontal Cores Collected	2-L Containers	Geotextile
1	2	2	Yes
2	2	2	Yes
3	0	3	Yes
4	1	5	Yes
5	1	4	Yes
6	2	4	Yes
15	0	3	No
16	2	2	Yes

Geotextile fabric was collected by cutting sections from the LCS pipes and storing these coupons in plastic containers. All samples of drainage sand and fabric were transported from the field at the end of each day and stored in a cold room at 4° C until analysis.

4.3.3 Sample Analysis

Characterization of the LCS materials included permeability, grain size distribution, volatile solids, and metals analysis for common constituents associated with chemical precipitation under landfill conditions. Table 4.2 lists the methods used in testing the above parameters.

TABLE 4.2. Methods for Characterizing Drainage Media

Parameters	Method
Permeability (Soil)	ASTM D 2434[1]
Permittivity (Geotextile)	ASTM D 4491[2]
Grain Size Distribution	ASTM D 422[3]
Volatile Solids	SM 209 F[4]
Metal Digestion	SW-846 Method 3050A[5]
Metals Analysis (Ca)	SW-846 Method 7140[5]
Metals Analysis (Fe)	SW-846 Method 7380[5]
Metals Analysis (Mg)	SW-846 Method 7450[5]
Metals Analysis (K)	SW-846 Method 7610[5]

[1] ASTM 1994c, [2] ASTM 1994d, [3] ASTM 1994a, [4] AWWA 1985, [5] U.S. EPA1994

4.3.4 Physical Characteristics

Found in this section is a description of each testing procedure utilized in this field study to determine the physical characteristics of the drainage sand and the geotextile sock

4.3.4.1 Soil Permeability

Clogging of a drainage material may be characterized by measuring the permeability of the soil and geotextile. From the perspective of LCS clogging, it is desirable to analyze samples in the exact condition as found in the field. Collection of such samples in the field was not found to be possible for this project. Typical permeability tests for sands and gravels involve reconstituting an air-dried soil sample in a permeameter and conducting a constant head permeability test. The actual mixing and air drying of such a sample may have an impact on the permeability by changing speciation of chemical precipitates and drying bacterial mass.

To minimize the impact of drying, the testing procedures employed here deviated from the standard method by testing the drainage sand without air drying prior to loading the permeameter. The goal of this method was to maintain as much as possible the biological and chemical characteristics of the samples during the testing procedures. Hydraulic conductivity tests were performed utilizing constant heads of 77, 62, and 37 cm and measuring the liquid flow through the column was measured. For comparison of the standard and modified test methods, additional samples were analyzed using the conventional ASTM D-2434 testing procedure. The analysis indicated that the modified method provided comparable results.

4.3.4.2 Geotextile Permittivity

The geofabrics were removed from the plastic containers and placed in a testing apparatus which conformed to the design specifications outlined in ASTM D-4491. A constant head was applied and the flow of liquid passing through the drainage material was measured. The samples of the geofabric were then “cleaned” by washing with an acidic solution followed by deionized water in an effort to restore the original characteristics of the material. The “cleaned” samples were then tested under analogous conditions.

4.3.4.3 Grain Size Distribution

Further characterization of the soil drainage layer included grain-size distribution analysis. Approximately 500 grams of sample were used to perform the analysis using a Lesson RX-86 shaker table and stainless steel sieves. Grain-size distributions for all drainage sand samples were compared using uniformity coefficients. The uniform coefficient (C_u) is a ratio of the grain diameter corresponding to 60% passing to the grain diameter corresponding to 10% passing (by weight). A C_u value of 1 indicates a poor distribution of grain sizes, while a C_u value greater than 15 indicates a well graded soil (Holtz and Kolvacs, 1981).

4.3.5 Chemical Characteristics of Drainage Sand

Found in this section is a description of each testing procedure utilized in this field study to determine the chemical l characteristics of the drainage sand.

4.3.5.1 Volatile Solids

Volatile solids analysis was performed on all soil samples. This test provides an approximation of the biological fraction of the solid sample by mass. Oven dried samples were mixed in a plastic container, weighed, and then placed in a muffle furnace at 550 ^{o}C to determine the volatile solids content. Similar volatile solids analysis was performed on all sieve fractions. As a result of small pieces of organic materials (plant roots) found in the LCS sand and borrow source, the volatile solids of the sand fraction passing a 0.85-mm sieve was used to characterize the sand.

4.3.5.2 Metals Analysis

An acid digestion procedure was used to prepare soil samples for metals analysis by flame atomic absorption spectroscopy. Through this aggressive eight-hour digestion process, the metals contained within one to two grams of sample are dissolved into solution. The solution was then filtered and analyzed on a Perkin Elmer 5100S Atomic Absorption Spectrophotometer for calcium, iron, magnesium, and potassium.

4.4 Results

4.4.1 Physical Characteristics

Results for the physical characterization of the sand drainage layer, including constant head hydraulic conductivity and grain size distribution, are listed in Table 4.3. Borrow samples are representative of the clean sand prior to exposure to landfill conditions.

4.4.1.1 Soil Permeability

The average hydraulic conductivity of the original borrow sand was determined to be 1.85 x 10^{-2} cm/sec. The hydraulic conductivity of all sand samples ranged from 9.72 x 10^{-3} to 1.83 x 10^{-2} cm/sec. Thus, the reduction in permeability of the sand drainage layer varied from 1% to 47%. However, the 47% reduction occurred in only one sample, and on average, the permeability of the drainage sand was 1.23 x 10^{-2} cm/sec. Thus, the average reduction in permeability was 33%.

4.4.1.2 Grain-size Distribution

Grain size distribution tests found uniformity coefficients to be close to one for all sand samples. This indicates that the sand drainage samples have poor gradation of particle sizes. As shown in Figure 4.4, the samples generally have a uniform particle size with diameters in the range of 0.1 to 0.3 mm (0.03 to 0.08 in). The soil corresponding to this diameter range is a medium to fine sand. Sand of this nature is highly permeable (hydraulic conductivity range of 1.0 x 10^{-2} to 1.0 x 10^{-3} cm/sec (Holtz and Kovacs, 1981). With the exception of one sample area, the presence of fine sand particles found in the LCS drainage sand, represented by D_{10}, did not increase due to exposure.

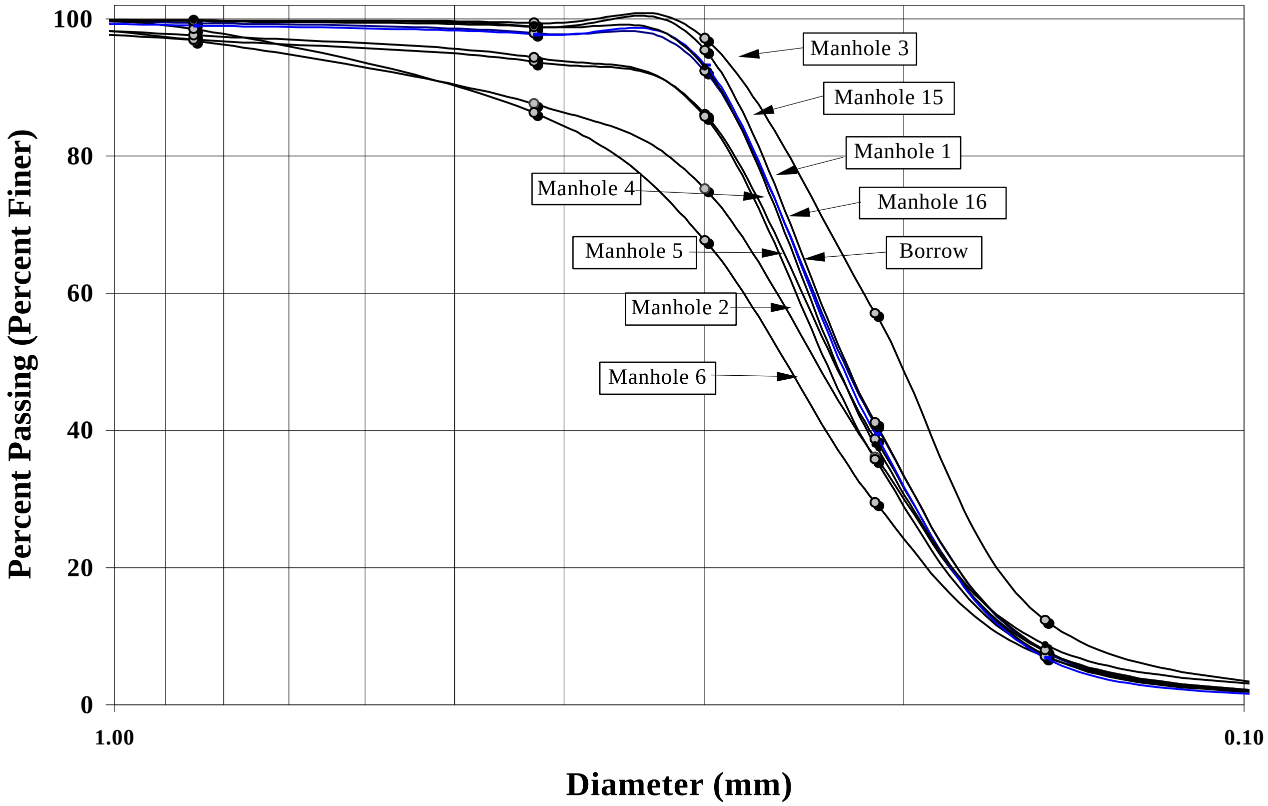

Figure 4.4 Grain Size Distributions

Table 4.3. Physical and Chemical Characteristics of Drainage Sand

Sample ID	Permeability (cm/sec)	Volatile Solids (<85 mm)	Uniformity Coefficient
MH 1- A	1.24E-02	0.20%	1.53
MH 1- B	1.04E-02	0.17%	1.48
MH 1- J1	1.12E-02	0.35%	1.48
MH 1- J2	1.02E-02	0.33%	1.47
MH 2- A	9.72E-03	0.36%	1.62
MH 2- B	1.13E-02	0.33%	1.65
MH 2- J1	1.29E-02	0.68%	1.67
MH 2- J2	1.23E-02	0.31%	1.69
MH 3- J1	1.16E-02	0.38%	1.41
MH 3- J2	1.17E-02	0.25%	1.45
MH 3- J3	1.83E-02	0.25%	1.53
MH 4- A	1.20E-02	0.27%	1.52
MH 4- J1	1.21E-02	0.92%	1.45
MH 4- J2	1.21E-02	0.98%	1.45
MH 4- J3	1.17E-02	0.40%	1.68
MH 5- A	1.22E-02	0.42%	1.50
MH 5- J1	1.09E-02	0.55%	1.52
MH 5- J2	1.04E-02	0.63%	1.54
MH 5- J3	1.03E-02	0.36%	1.58
MH 6- A	1.32E-02	0.52%	1.80
MH 6- B	1.67E-02	0.64%	1.70
MH 6- J1	1.32E-02	0.65%	1.61
MH 6- J2	1.42E-02	0.78%	1.70
MH 6- J3	1.58E-02	0.76%	1.67
MH 15- J1	1.23E-02	0.35%	1.53
MH 15- J2	1.37E-02	0.45%	1.44
MH 15- J3	1.29E-02	0.20%	1.41
MH 16- A	1.16E-02	0.25%	1.50
MH 16- B	1.25E-02	0.19%	1.45
MH 16- J1	1.27E-02	0.50%	1.45
MH 16- J2	1.19E-02	0.31%	1.46
Sample Avg.	1.23E-02	0.44%	1.55
Borrow 1	---	0.20%	1.61
Borrow 2	---	0.30%	1.59
Borrow 3	1.89E-02	0.10%	1.39
Borrow 4	1.75E-02	0.30%	1.59
Borrow 5	1.92E-02	0.20%	1.61
Borrow Avg.	1.85E-02	0.22%	1.56

4.4.2 Chemical Characteristics of Drainage Sand

Results for the chemical characterization of the sand drainage layer, including volatile solids and metals analysis are presented in this section.

4.4.2.1 Volatile Solids

The drainage sand generally had a higher volatile solids content compared to the borrow sources. The average volatile solids content for the borrow sand was 0.22%, while the average volatile solids content of the drainage sand was 0.44%, ranging from 0.13% to 0.98%. The means were statistically different at the 99% confidence interval. The slight increase in volatile solids might be indicative of the growth of some biomass, but may also result from soluble organic matter in the leachate collected as part of the sample. Regardless, none of the collected samples were visibly clogged or agglomerated by biomass, as reported in other studies.

4.4.2.2 Metals Analysis

Table 4.4 presents the results for metals analysis of the sand drainage layer. The major contributing constituents for chemical precipitation in leachate collection systems (Ca, Fe, Mg, K) were analyzed. Precipitation of calcium carbonate and ferrous salts due to sulfate-reducing bacteria has been shown to clog drainage media (Rohde and Gribb 1990, Rittman et al. 1996).

The average concentrations for Ca, Fe, Mg, and K in the borrow sand was 10.9, 142.7, 4.1, and 29.2 mg/kg, respectively. The LCS sand had average concentrations of 881.7 mg/kg for calcium, 458.4 mg/kg for iron, 101.9 mg/kg for magnesium, and 96.0 mg/kg for potassium. With the exception of three samples analyzed for potassium the metal concentrations for all landfill samples were greater than the borrow sand samples.

As with the volatile solids, this may also be a result of dissolved ions in the leachate collected as part of the sample. However, some samples did contain visible areas of discoloration, typically black in nature. This has been observed in other LCS clogging studies and has been attributed to iron or other metal precipitates as sulfides (Koerner et. al 1993, Rittman et. al 1996, and Rowe et. al 1995). The areas of discoloration were not continuous, but occurred rather as distinct zones and again did not agglomerate the sand in a cemented nature.

TABLE 4.4 Metal Concentration in Soil Drainage Media

Sample ID	Calcium (mg/kg)	Iron (mg/kg)	Magnesium (mg/kg)	Potassium (mg/kg)
MH 1- A	2827.7	448.1	114.8	21.9
MH 1- B	10,503.9	560.1	742.1	73.2
MH 1- J1	5216.8	719.6	174.4	30.7
MH 1- J2	2390.8	331.5	84.2	24.4
MH 2- A	119.0	445.9	71.0	101.7
MH 2- B	445.0	904.8	146.6	345.2
MH 2- J1	392.0	812.6	141.3	88.4
MH 2- J2	106.8	472.3	50.1	101.4
MH 3- J1	202.3	495.2	38.6	48.1
MH 3- J2	113.3	365.9	29.4	32.7
MH 3- J3	154.1	378.3	32.3	37.2
MH 4- A	582.9	743.4	96.0	78.0
MH 4- J1	479.0	641.4	85.3	64.2
MH 4- J2	618.7	631.4	98.5	66.9
MH 4- J3	208.6	248.7	75.5	71.1
MH 5- A	257.3	418.4	129.4	225.2
MH 5- J1	247.3	369.7	85.23	134.6
MH 5- J2	464.5	541.2	133.4	218.8
MH 5- J3	544.0	627.2	144.3	206.6
MH 6- A	249.8	423.2	191.3	210.7
MH 6- B	75.1	286.2	50.1	126.3
MH 6- J1	74.2	311.3	61.9	128.0
MH 6- J2	64.0	217.9	47.6	82.1
MH 6- J3	177.2	373.1	66.6	66.1
MH 15- J1	65.8	294.7	23.6	52.1
MH 15- J2	77.9	325.2	27.8	60.5
MH 15- J3	72.3	313.1	27.7	51.5
MH 16- A	178.9	378.0	66.2	81.8
MH 16- B	155.0	371.2	26.5	20.9
MH 16- J1	131.9	360.2	61.8	92.8
MH 16- J2	136.6	430.7	32.7	37.0
Sample Avg.	881.7	458.4	101.9	96.0
Borrow 1	9.0	121.1	10.4	27.5
Borrow 2	10.8	162.1	1.2	25.5
Borrow 3	7.7	119.7	0.0	21.8
Borrow 4	10.9	159.6	4.3	35.1
Borrow 5	15.8	150.9	4.5	35.9
Borrow Average	10.9	142.7	4.1	29.2

4.4.3 Geotextile Permittivity

Initial inspection of the geotextile upon removal from the LCS pipes found small amounts of black slime and sand embedded in the woven material. Table 4.4 lists the results of permittivity testing for both collected geofabrics and "cleaned" samples. Relative to the clean samples, the geotextile permittivity had a minimum reduction of 2%(MH 5) and a maximum reduction of 75% (MH 6). The average reduction was determined to be from 6.4 sec^{-1} to 3.3 sec^{-1}. Although some reduction in permittivity was measured, in many of the samples, the maximum reduction corresponded to a permittivity value of 1.6 sec^{-1}. This permittivity value was still large enough to provide the necessary flow capacity.

Table 4.4. Geotextile Permittivity

Sample	Sample Permittivity (sec^{-1})	"Cleaned"Sample Permittivity (sec^{-1})
MH 1	2.0	6.3
MH 2	2.3	5.5
MH 3	6.6	7.2
MH 4	2.6	5.6
MH 5	7.6	7.7
MH 6	1.6	6.2
MH 16	1.9	6.2

4.5 DISCUSSION OF LCS CLOGGING

Some degree of clogging was observed in both the drainage sand samples (33% average reduction in hydraulic conductivity) and the geofabrics (48% average reduction in permittivity). To examine these reductions in the perspective of current design practices, it is helpful to determine the factor of safety (FS) that would have been necessary to compensate for the degree of clogging that was measured. The FS is defined as the following (Koerner 1994):

$$FS = \frac{K_{ALLOWED}}{K_{REQUIRED}}$$

The term $K_{REQUIRED}$ represents the required value for a given design parameter, while $K_{ALLOWED}$ is the allowable value for the design parameter. The results indicate that an average FS of 1.5 (maximum of 2.0) for the drainage sand and an average FS of 2.0 (maximum of 4.0) for the geotextiles would have been required to predict the degree of clogging that occurred at this landfill within a six year period. The current literature indicates that the use of a FS in the range of 10 to 100 (one to two orders of magnitude) should be applied to landfill drainage material to account for long-term clogging effects (Koerner and Koerner 1995). Therefore, although measurable clogging was observed, it was lower than that typically accounted for in current landfill design practices.

No definitive conclusion on the exact mechanisms of clogging was made. Some metal precipitation was observed, and elevated levels of iron and calcium are consistent with literature reports of precipitates of these two chemicals as clogging agents (Rittman et. al 1996, Rowe et. al 1995). Organic content was elevated, but was small relative to the mass of sand. It is likely that both of these phenomena contributed to permeability reduction; however, no cementation or agglomeration of sand particles had occurred. It should be noted that the LCS samples collected for this study were representative of the middle of the drainage layer. While some literature (Rohde and Gribb, 1990) indicates that clogging often occurs at the boundary between the waste and the drainage media, it is the drainage media above the liner that dictates the head on the liner.

4.5.1 Impact on LCS Performance

As previously discussed, the permeability of the leachate collection system is a primary factor in determining the collection efficiency. The purpose of this study was to examine the conditions of drainage media collected from an operating landfill to assess the degree of clogging (reduction in permeability and permittivity). From the analysis of drainage sand and geotextile samples it was determined that both displayed some degree of clogging. To assess the impact of this degree of clogging on the LCS performance at this site, head on the liner was calculated based on a drainage sand hydraulic conductivity of both the average borrow sand and the average sample. The Modified Giroud Equation (Giroud and Houlihan, 1995) was utilized to estimate the head on the liner:

$$\frac{h_{\max}}{L} = \left(\frac{\sqrt{1+4l}-1}{2} \times \frac{\tan a}{\cos a} \right) \times j$$

where,

$$l = \frac{e}{k \cdot \tan^2 a}$$

$$j = 1 - .12\exp\left\{ - \left[\log\left(\frac{8l}{5} \right)^{5/8} \right]^2 \right\}$$

The initial and “clogged” permeability values for hydraulic conductivity (k) used were 1.85 x 10^{-2} and 1.23 x 10^{-2} cm/sec, respectfully. The length of one side of the collection area (L) was 45.7 m (150 ft). The slope of the collection area (α) was 1%. The average impingement rate (e) was based upon maximum monthly flow conditions at the landfill and was determined to be 0.6 L/m^2-day (666. 7 gal/acre-day). The calculated head on the liner for initial LCS conditions was 7.4 cm (2. 9 in) and 10.7 cm (4.2 in) after seven years of exposure to landfill conditions. Although additional clogging may occur over the life of the landfill, the flowrate will decrease dramatically with the installation of a cap. Thus, any further clogging of the LCS would likely be offset by a decrease in flow.

4.6 Conclusions

The analysis of drainage media from an operating landfill leachate collection system indicated that some clogging had occurred after six year of exposure. No definitive mechanism could be identified, but chemical precipitation and perhaps biological activity contributed. The Modified Giroud Equation estimated that clogging mechanisms caused a head increase of 3.2 cm (1.3 in) on the liner; however, the resulting head on the liner, 10.7 cm (4.2 in), was well within the 30 cm requirement. Similarly, the factors of safety suggested in recent literature account for one to two orders of magnitude clogging effects. The results indicated that clogging effects for this six-year old landfill would likely be accounted for with average factors of safety of 1.5 and 2.0 for the drainage sand and geotextile, respectively. Thus, current practices for landfill design (FS = 10 to 100) should adequately account for long-term clogging effects at landfills of a similar nature as studied here.

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5. RECOMMENDATIONS

5.1 LCS Clogging Field Study Design

The most direct method to assess clogging of Florida LCSs would be to conduct a field study of LCS performance. This field study should consist of several test cells located through out the state of Florida. Site selection should be based on representing the full range of climates which can be anticipated in Florida. These test cells should be constructed with identical leachate collection systems. The leachate collection systems should contain a dense array of pressure transducers for the measurement of leachate head within the liner. Particular care should be made to ensure readings on both sides of material interfaces. In addition to monitoring leachate head, precipitation data and leachate production rates should be monitored. It will also be important to determine through laboratory testing the amount and size distribution of fines released by both the materials in the LCS and the placed waste. Monitoring the particles produced with the leachate outflow will then provide the information required to conduct a phenomenological, mass balance approach to the entrapment of fines within the LCS. This information will lead fairly directly to the estimation of permeability decreases which could be expected from particle transport and deposition. Permeability decreases in excess of this estimated could then be attributed to biological growths and chemical precipitates.

APPENDIX A - SURVEY SUMMARIES

SURVEY OF EXISTING LANDFILL LEACHTE COLLECTION SYSTEMS

Table 1: Design Life / Date

Landfill Names	Design Life / Date
North Central , Polk County	NA
Phase 1	96/97
Phase 2	NA
Southeast Sanitary, Polk County	12/17/97
NW Waste Mgmt. Facility, Hernando County	10/1/94
Central County Solid Waste Disposal Complex, Sarasota	5/10/96
Desoto County Section 16	9/9/88
Sumter County	1994-1996
1 Citrus Central, Class 1, Citrus County	1994 - ?
Osceola County, Southport Landfill --- Phase III	1993 - 2001
Orange County Landfill --- Cell 8	1989 - 2002
Indian River County L.F. --- Segment 2	1991 - ?
Baseline L.F. --- PHASE III-B	Mar-93
Suwanee County L.F.	
New River Regional L.F.	Jun-92
Cell 1	Feb-95
Cell 2	89-90
Hamilton County Sanitary L.F.	1991
Aucilla Area SW Facility	Sep-92
Jefferson/Smurfit L.F.	1986
Madison County L.F.	
Winfield, Columbia County	Jul-92
Cell 1	Jul-95
Cell 2	Mar-91
North Sanitary L.F., Jacksonville	Mar-96
West Nassau L.F.	10/1/1996 built in 92
Trail Ridge L.F. , Duvall County	4/29/86
Rosemary Hill L.F.	3/14/95
Tillman Ridge L.F.	

Table 2: Design

Landfill Names	Design Firm
North Central , Polk County	
Phase 1	Envisors, Inc.
Phase 2	PBS & J
Southeast Sanitary, Polk County	Envisors, Inc.
NW Waste Mgmt. Facility, Hernando County	Coastal Eng. Assoc. / Brown & Caldwell
Central County Solid Waste Disposal Complex, Sarasota	CDM, Sarasota
Desoto County Section 16	SCS Engineers
Sumter County	Springstead Engineering Inc.
1 Citrus Central, Class 1, Citrus County	CH2M Hill
Osceola County, Southport Landfill --- Phase III	Ardaman & Associates
Orange County Landfill --- Cell 8	HDR
Indian River County L.F. --- Segment 2	CDM
Baseline L.F. --- PHASE III-B	Jones, Edmunds, & Associates
Suwanee County L.F.	Environmental Science & Engineering
New River Regional L.F.	
Cell 1	Darabi & Associates
Cell 2	Darabi & Associates
Hamilton County Sanitary L.F.	Smith & Gillespie
Aucilla Area SW Facility	Darabi & Associates
Jefferson/Smurfit L.F.	Law Environmental
Madison County L.F.	Gulf Coast Engineering
Winfield, Columbia County	
Cell 1	Darabi & Associates
Cell 2	Darabi & Associates
North Sanitary L.F., Jacksonville	PBS & J
West Nassau L.F.	AMA Environmental Service
Trail Ridge L.F. , Duvall County	England, Thims & Miller
Rosemary Hill L.F.	England, Thims & Miller
Tillman Ridge L.F.	HDR Engineering, Inc.

Table 3: Leachate Collection System

Landfill Names	Type of LCS
North Central , Polk County	
Phase 1	NA
Phase 2	Double
Southeast Sanitary, Polk County	Composite
NW Waste Mgmt. Facility, Hernando County	Double

Central County Solid Waste Disposal Complex, Sarasota	Composite w / Geonet
Desoto County Section 16	Double FML / Geonet
Sumter County	Composite
1 Citrus Central, Class 1, Citrus County	Double Geomembrane
Osceola County, Southport Landfill --- Phase III	Composite
Orange County Landfill --- Cell 8	Composite
Indian River County L.F. --- Segment 2	Composite
Baseline L.F. --- PHASE III-B	Double liner
Suwanee County L.F.	Composite
New River Regional L.F.	
Cell 1	Composite
Cell 2	Double
Hamilton County Sanitary L.F.	Composite
Aucilla Area SW Facility	Composite
Jefferson/Smurfit L.F.	Double
Madison County L.F.	Composite
Winfield, Columbia County	
Cell 1	Double with HDPE drainage net
Cell 2	Double with 0.25" HDPE drainage net
North Sanitary L.F., Jacksonville	Double with protective soil
West Nassau L.F.	Composite with geonet
Trail Ridge L.F. , Duvall County	Double
Rosemary Hill L.F.	Composite
Tillman Ridge L.F.	composite/double

Table 4: Liner Material

Landfill Names	Material
North Central , Polk County	
Phase 1	60mil HDPE
Phase 2	NA
Southeast Sanitary, Polk County	60mil HDPE
NW Waste Mgmt. Facility, Hernando County	HDPE Type 2
Central County Solid Waste Disposal Complex, Sarasota	60mil HDPE
Desoto County Section 16	60mil HDPE
Sumter County	NA
1 Citrus Central, Class 1, Citrus County	HDPE
Osceola County, Southport Landfill --- Phase III	60mil HDPE
Orange County Landfill --- Cell 8	60mil HDPE
Indian River County L.F. --- Segment 2	60mil HDPE
Baseline L.F. --- PHASE III-B	60mil HDPE
Suwanee County L.F.	60 mil Fml
New River Regional L.F.	
Cell 1	60mil HDPE
Cell 2	0.06" HDPE
Hamilton County Sanitary L.F.	30 mil PVC on side slope only
Aucilla Area SW Facility	60mil HDPE
Jefferson/Smurfit L.F.	60mil HDPE
Madison County L.F.	30 mil PVC on side slope only
Winfield, Columbia County	
Cell 1	60 mil HDPE
Cell 2	0.06" HDPE
North Sanitary L.F., Jacksonville	60 mil HDPE
West Nassau L.F.	60 mil HDPE
Trail Ridge L.F. , Duvall County	60 mil HDPE
Rosemary Hill L.F.	60 mil HDPE
Tillman Ridge L.F.	60 mil HDPE

Table 5: Slope of Drainage Length

Landfill Names	Slope (%)
North Central , Polk County	
Phase 1	2
Phase 2	2
Southeast Sanitary, Polk County	2
NW Waste Mgmt. Facility, Hernando County	5
Central County Solid Waste Disposal Complex, Sarasota	2
Desoto County Section 16	2
Sumter County	1.62
1 Citrus Central, Class 1, Citrus County	2 - 1.15
Osceola County, Southport Landfill --- Phase III	0.4
Orange County Landfill --- Cell 8	2
Indian River County L.F. --- Segment 2	2
Baseline L.F. --- PHASE III-B	2
Suwanee County L.F.	2
New River Regional L.F.	
Cell 1	2
Cell 2	2
Hamilton County Sanitary L.F.	2
Aucilla Area SW Facility	3.08 & 2
Jefferson/Smurfit L.F.	3 & 2
Madison County L.F.	1
Winfield, Columbia County	
Cell 1	2 & 3.08
Cell 2	2 & 3.1
North Sanitary L.F., Jacksonville	2
West Nassau L.F.	2
Trail Ridge L.F. , Duvall County	2
Rosemary Hill L.F.	0.5
Tillman Ridge L.F.	1.05

Table 6: Slope of Collection Pipe

Landfill Names	Slope (%)
North Central , Polk County	
Phase 1	0.2
Phase 2	NA
Southeast Sanitary, Polk County	0.2
NW Waste Mgmt. Facility, Hernando County	1
Central County Solid Waste Disposal Complex, Sarasota	0.2
Desoto County Section 16	0.55
Sumter County	0.34
1 Citrus Central, Class 1, Citrus County	NA
Osceola County, Southport Landfill --- Phase III	0.4
Orange County Landfill --- Cell 8	1- 0.35
Indian River County L.F. --- Segment 2	NA
Baseline L.F. --- PHASE III-B	NA
Suwanee County L.F.	0.5
New River Regional L.F.	
Cell 1	1
Cell 2	1
Hamilton County Sanitary L.F.	0.5
Aucilla Area SW Facility	1.5
Jefferson/Smurfit L.F.	0.5
Madison County L.F.	0.6
Winfield, Columbia County	
Cell 1	1
Cell 2	0.5
North Sanitary L.F., Jacksonville	1
West Nassau L.F.	0.5
Trail Ridge L.F. , Duvall County	.85 & 1.15
Rosemary Hill L.F.	0.6, 0.9, 1.0, 1.3
Tillman Ridge L.F.	0.17-0.2

Table 7: Pipe Spacing (center to center)

Landfill Names	Spacing (ft)
North Central , Polk County	
Phase 1	596
Phase 2	400
Southeast Sanitary, Polk County	478
NW Waste Mgmt. Facility, Hernando County	200
Central County Solid Waste Disposal Complex, Sarasota	400
Desoto County Section 16	205 - 520
Sumter County	370
1 Citrus Central, Class 1, Citrus County	300
Osceola County, Southport Landfill --- Phase III	200
Orange County Landfill --- Cell 8	200
Indian River County L.F. --- Segment 2	180
Baseline L.F. --- PHASE III-B	100
Suwanee County L.F.	50
New River Regional L.F.	
Cell 1	100
Cell 2	100
Hamilton County Sanitary L.F.	140
Aucilla Area SW Facility	100
Jefferson/Smurfit L.F.	60
Madison County L.F.	150 & 275
Winfield, Columbia County	
Cell 1	100
Cell 2	100
North Sanitary L.F., Jacksonville	200
West Nassau L.F.	100
Trail Ridge L.F. , Duvall County	300
Rosemary Hill L.F.	365 to 402.5
Tillman Ridge L.F.	210

Table 8: Type of Pipe

Landfill Names	Type
North Central , Polk County	
Phase 1	Perforated 8" PVC
Phase 2	NA
Southeast Sanitary, Polk County	Perforated 8" HDPE
NW Waste Mgmt. Facility, Hernando County	Perforated 8" HDPE
Central County Solid Waste Disposal Complex, Sarasota	Perforated 8" HDPE
Desoto County Section 16	Perforated 8" HDPE
Sumter County	Perforated 6”
1 Citrus Central, Class 1, Citrus County	NA
Osceola County, Southport Landfill --- Phase III	15 - Perforated 6” ADS Pipe
Orange County Landfill --- Cell 8	12 - Perforated 8” HDPE Pipe, SDR 13.5
Indian River County L.F. --- Segment 2	12 - Perforated 6” HDPE Pipe
Baseline L.F. --- PHASE III-B	Perforated 8” collection, 6” leak detection
Suwanee County L.F.	8" HDPE
New River Regional L.F.	
Cell 1	8" HDPE
Cell 2	8" HDPE SDR
Hamilton County Sanitary L.F.	Schedule 80 6" HDPE
Aucilla Area SW Facility	8" HDPE
Jefferson/Smurfit L.F.	HDPE 4" for secondary 6" for primary
Madison County L.F.	PVC 4", SDR 35
Winfield, Columbia County	
Cell 1	HDPE
Cell 2	8" HDPE
North Sanitary L.F., Jacksonville	NA
West Nassau L.F.	8" HDPE
Trail Ridge L.F. , Duvall County	8" HDPE
Rosemary Hill L.F.	6" DIA polyethylene AASATO M-252
Tillman Ridge L.F.	8" HDPE

Table 9: Pipe 'Socked' or 'Burrito' wrapped

Landfill Names	Type
North Central , Polk County	
Phase 1	Socked, later changed to burrito
Phase 2	NA
Southeast Sanitary, Polk County	Burrito
NW Waste Mgmt. Facility, Hernando County	Burrito
Central County Solid Waste Disposal Complex, Sarasota	Burrito
Desoto County Section 16	Burrito
Sumter County	Burrito
1 Citrus Central, Class 1, Citrus County	Burrito
Osceola County, Southport Landfill --- Phase III	Burrito
Orange County Landfill --- Cell 8	Burrito
Indian River County L.F. --- Segment 2	Burrito
Baseline L.F. --- PHASE III-B	Burrito
Suwanee County L.F.	Quasi burrito later indicated wrapping
New River Regional L.F.	
Cell 1	Burrito
Cell 2	Burrito
Hamilton County Sanitary L.F.	Burrito
Aucilla Area SW Facility	Burrito
Jefferson/Smurfit L.F.	neither
Madison County L.F.	Burrito
Winfield, Columbia County	
Cell 1	Burrito
Cell 2	Burrito
North Sanitary L.F., Jacksonville	Burrito
West Nassau L.F.	Burrito
Trail Ridge L.F. , Duvall County	neither
Rosemary Hill L.F.	Burrito
Tillman Ridge L.F.	Burrito

Table 10: Geotextile Use

Landfill Names	Used
North Central , Polk County	
Phase 1	Filter Fabric
Phase 2	NA
Southeast Sanitary, Polk County	yes
NW Waste Mgmt. Facility, Hernando County	yes
Central County Solid Waste Disposal Complex, Sarasota	yes
Desoto County Section 16	yes, non woven
Sumter County	yes
1 Citrus Central, Class 1, Citrus County	yes,
Osceola County, Southport Landfill --- Phase III	yes
Orange County Landfill --- Cell 8	yes
Indian River County L.F. --- Segment 2	yes, non woven
Baseline L.F. --- PHASE III-B	yes
Suwanee County L.F.	yes
New River Regional L.F.	
Cell 1	yes
Cell 2	yes
Hamilton County Sanitary L.F.	yes
Aucilla Area SW Facility	yes
Jefferson/Smurfit L.F.	yes
Madison County L.F.	yes
Winfield, Columbia County	
Cell 1	yes
Cell 2	yes
North Sanitary L.F., Jacksonville	yes
West Nassau L.F.	yes
Trail Ridge L.F. , Duvall County	yes
Rosemary Hill L.F.	yes, non woven
Tillman Ridge L.F.	yes

Table 11: Drainage material used

Landfill Names	Type
North Central , Polk County	
Phase 1	NA
Phase 2	NA
Southeast Sanitary, Polk County	24" sand
NW Waste Mgmt. Facility, Hernando County	24" sand & rock
Central County Solid Waste Disposal Complex, Sarasota	24" sand
Desoto County Section 16	24" sand & # 3 stone
Sumter County	sand & gravel
1 Citrus Central, Class 1, Citrus County	NA
Osceola County, Southport Landfill --- Phase III	24" sand
Orange County Landfill --- Cell 8	24" sand
Indian River County L.F. --- Segment 2	24" sand
Baseline L.F. --- PHASE III-B	24" sand
Suwanee County L.F.	Sand & protective soil layer over
New River Regional L.F.	
Cell 1	24" sand
Cell 2	24" sand
Hamilton County Sanitary L.F.	sand & gravel
Aucilla Area SW Facility	sand
Jefferson/Smurfit L.F.	sand
Madison County L.F.	clean sand
Winfield, Columbia County	
Cell 1	sand & gravel
Cell 2	sand 7 gravel
North Sanitary L.F., Jacksonville	round river rock and protective soil
West Nassau L.F.	drainage aggregate,sand,protective soil
Trail Ridge L.F. , Duvall County	aggregate- aash to # 3, sand
Rosemary Hill L.F.	Crusted stone & protective soil
Tillman Ridge L.F.	aggregate,gravel,sand

Regulator Questions

Question 1: What leachate head do you consider standard for a LCS design?

Regulatory District	Answer
South District	
Northwest District	1ft.
Northeast District	1ft.
Southwest District	1ft.
Southeast District	1ft.
	1ft.

Question 2: Do you require monitoring of leachate head? If so, do you know of any landfills that monitor leachate head.

Regulatory District	Answer
South District	no
Northwest District	no
Northeast District	no, We ask facilities to supply leachate data.
Southwest District	no, but require landfills to submit leachate data.
Southeast District	Yes, only over a double lined landfill Chambers, Okeechobee -- Palm Beach County

Question 3: Do you require LCS maintenance? If so, how often?

Regulatory District	Answer
South District	no ,only if something is wrong
Northwest District	yes, only as necessary
Northeast District	yes, only twice a year
Southwest District	yes, video and flush their lines during the permit review
Southeast District	yes, require video taping of pipes once a year.

Question 4: How do you estimate the design flow rate of leachate to the LCS?

Regulatory District	Answer
South District	doesn't do this, the engineer does
Northwest District	The consultant does this with the help model
Northeast District	The consultant does this with the help model
Southwest District	This is based on runoff coefficient, vegetation, closed,open or active cell. Told me to talk to Kim Ford.
Southeast District	Engineer answers this.

Question 5: What type of leachate piping system do you recommend?

Regulatory District	Answer
South District	Recommends a geonet, but not really required.
Northwest District	This is a design option of the engineer
Northeast District	This is site specified.
Southwest District	This is a design option of the engineer
Southeast District	Engineer answers this.

Question 6: What types of design equations do you recommend for LCS design?

Regulatory District	Answer
South District	HELP --it is good for design, but not good in the field, also added that HELP is under attack
Northwest District	This for the engineer to answer
Northeast District	Mentioned J.P. Giroude equations
Southwest District	This for the engineer
Southeast District	This for the engineer

Question 7: Are factors of safety required for any components?

Regulatory District	Answer
South District	didn't know
Northwest District	Engineer answers this also
Northeast District	Design Engineer answers this.
Southwest District	Don't know.
Southeast District	They are recommended but not required

Question 8: Is the biological clogging of the LCS a concern?

Regulatory District	Answer
South District	Not Sure, Chemical clogging is though because of the mills
Northwest District	No, ash clogging has occurred as a result of human error- the person neglected to open the valves.
Northeast District	yes
Southwest District	Says that clogging is present but doesn't know if it is bioclogging
Southeast District	yes

Question 9: How do you verify that the materials you specify are being used?

Regulatory District	Answer
South District	Go out to L.F while it is being constructed. Quality control and Quality assurance by a third party. The engineer signs off on it.
Northwest District	Quality control and Quality assurance by a third party
Northeast District	First is the submission of a permit application, then the landfill submits a certificate signed by a P.E. Site inspections are done regularly.
Southwest District	Quality control and Quality assurance by a third party. Do inspections during the construction phase.
Southeast District	Quality control and Quality assurance by a third party.

DATA ON DESIGNERS / CONSULTANTS CONTACTED

Question 1: What is the estimated flow rate of leachate to the LCS& How do you estimate Leachate flow rates?

Contact	Answer
A	22,000gal/acre/month, Using the HELP model
B	60,000 gal/day Using the HELP model
C	NA Using the HELP model.
D	600gal/acre/day Using the HELP model
E	800gal/acre/day NA
F	800 - 1000 gpd/acre. Using the HELP model.

Question 2: What amount of leachate head on the liner did you design the LCS for?

Contact	Answer
A	1’
B	1’
C	1’
D	9”
E	1’
F	9”

Question 3: What type of liner did you utilize?

Contact	Answer
A	HDPE
B	In-situ phosphatic clays ranging in thickness from 4- 18’. Also used 36 mil Hypalon around the perimeter berm only
C	60 mil HDPE over 2 ft of 1E^-7 cm/s compacted clay.
D	Double liner system.
E	60 mil HDPE
F	Double liner, 60 mil HDPE

Question 4: How far apart are the LCS pipes spaced?

Contact	Answer
A	200’ max, but generally less.
B	Varies because of a complex system with
C	gravel trenches and pipe trenches. Phase I, II, III avg. 200’, Phases IV,V, VI avg. 400’.
D	100 - 200’.
E	60 to 100’.
F	100’
	60’.

Question 5: What type and size of pipe did you utilize to collect and transport the leachate & what is the slope?

Contact	Answer
A	6, or 8” pipe for collection, 4” to transport, slope should be no less
B	Phases 1,2,3, and 4 have 8” diameter PVC since designed in 1983.
C	Phases 5 & 6 have 8” diameter HDPE since designed in 1992. The slope varies from 0 to 2 %.
D	Schedule 80(typically) PVC 6” diameter for most pipes and 8” for major headers. Slope = ½%.
E	HDPE # 3406, 6” collection pipe, 8” main header slope from .55% to 1 %.
F	SDR 11 to 15, HDPE, min of 4” laterals, 6 to 8” header piping. Slope is from 1 - 2 %. SDR 15.5 , 6 “ diameter for laterals, 8” for headers.

Question 6: Are the pipes perforated or slotted?

Contact	Answer
A	perforated
B	perforated
C	perforated
D	perforated
E	perforated
F	perforated

Question 7: Are pipes socked with a geotextile? If so, what type and what is its permeability

Contact	Answer
A	No
B	No
C	Yes, NA
D	No
E	No
F	No

Question 8: What is the slope of the LCS?

Contact	Answer
A	same as slope of the pipe
B	Same as above
C	0.5% pipes, 0.5 - 2 % liner base.
D	0.2 to 0.5 %
E	same as slope of the pipe
F	0.55 - 1 %

Question 9: What type of filter material did you utilize?

Contact	Answer
A	Use both woven & non - woven
B	Granite rock
C	FDOT No. 5, 1 x 10^-2. Not verified.
D	Non- woven geotextile above the drainage layer.
E	8 oz non - woven needle punched geotextile, polypropylene.
F	Sand above the liner, min. of 1E-3 cm/sec

Question 10: What type of drainage material did you use?

Contact	Answer
A	Geonet, sand
B	Sand at 1x10^-3. Verified by doing infiltrometer tests and permeability tests
C	Crushed stone with a high K is preferred, but granular material sand (K=1E-3) might be used.
D	River rock, sand.
E	Rounded river rock
F	River rock

Question 11: Are geotextiles used in the LCS?

Contact	Answer
A	That depends, some people like them and some people don't.
B	Non woven around the rock.
C	No
D	Yes, a geonet, an 8 oz geotextile leachate pipe envelope.
E	No
F	No

Question 12: Are the geotextiles treated with a biocide?

Contact	Answer
A	Yes
B	No
C	No
D	No
E	No
F	No

Question 13: In designing the LCS, are safety factors used? If so, for what components of the LCS?

Contact	Answer
A	Yes – use HELP model. The head on the liner should have a 150% F.S.
B	No
C	Yes Drainage material and the filter. Based on Koerner and Koerner,. a 2 order magnitude decrease in permeability is assumed
D	Yes For 6" pipe a F.S. of 2, Header pipe F.S. of 1.5, .2"Geonet use F.S. of 2.
E	Yes Piping system
F	Yes 1.3 for leachate header and geotextile, 2.0 for leachate laterals

Question 14: Is bio-clogging of LCS pipes addressed in the LCS design?

Contact	Answer
A	Not really a problem, it needs to be designed so that it is resistant to biological growth. The L.F. operator needs to flush the pipes twice a year
B	Provided perimeter cleanouts
C	No
D	yes, but doesn't know how to prevent it.
E	No
F	No

Question 15: Have you experienced any design or installation problems in the past?

Contact	Answer
A	Yes, but not on his design. A cap in palm beach county had a 20 mil thickness, but it needed to be 40 mil or greater.
B	No
C	Mechanical crushing of LCS pipes can be a problem.
D	No
E	Yes, only for corrugated and PVC piping.
F	No

Question 16: Is flushing included or recommended in the design of the LCS?

Contact	Answer
A	Yes, twice a year.
B	Yes, with water jetting. They are cleaned as needed if poor performance is observed.
C	Yes
D	Yes
E	Yes, annually.
F	Yes, annually.

Question 17: Do you measure leachate head and monitor it?

Contact	Answer
A	No
B	Yes, with piezometers
C	Yes. Measurements are usually made at the sump by direct means.
D	No
E	No
F	No

Question 18: Are some parts of the landfill design more regulated than others?

Contact	Answer
A	Liner system is most important, the clay liner is regulated very strongly. The head on the liner is also strongly regulated.
B	No, everything is regulated
C	The head on the liner is also strongly regulated. The design should be left to good engineering judgment and practice..
D	Liner system is most important, The head on the liner is also strongly regulated
E	No. the most important is the pipe sizing, settling and crushing potential.
F	Yes, the Liner , drainage sand, and pipe system. Most important components are the geomembrane, sub-base, pipe strength and flexibility, and geotextile apparent opening size.

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