AN ASSESSMENT OF LANDFILL COVER SYSTEM SOIL BARRIER LAYER HYDRAULIC PERFORMANCE

FINAL PAPER

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STATE OF MAINE

prepared by

Bureau of Remediation and Waste Management
Division of Technical Services
Solid Waste Engineering Unit

May 2001

Abstract

Although compacted, fine grained soils have been used as a hydraulic barrier to cover waste disposal sites for many years, their life cycle hydraulic performance has long been questioned. During 1993, the State of Maine Department of Environmental Protection (Department) initiated a field and laboratory testing program to assess the in-service hydraulic condition of fine grained soils used as the sole barrier layer within municipal solid waste landfill cover systems. The sites were selected based on the amount of quality control and quality assurance testing conducted during closure construction and the quality of available documentation. Four sites with soil barriers were tested between 1993 and 1998. Field testing was conducted using a Sealed Double-Ring Infiltrometer (SDRI) in accordance with ASTM D 5093-90. A minimum of two field tests were performed at each site during varying stages of the final cover system service life. For comparison, laboratory triaxial testing of thin-walled tube barrier soil samples was conducted in accordance with ASTM D 5084-90. Comparisons between the two test methods were made in order to assess the validity of reliance on thin-walled tube sample results as indicators of hydraulic performance. Preliminary comparisons were made regarding the hydraulic degradation over time of marine silty clay versus glacial till barrier layers.

The results of the study clearly demonstrate that all four soil barriers have been undergoing degradation, with an associated loss of hydraulic properties. The known and suspected contributory factors to the barrier soil degradation process are discussed. Recommendations to improve the current state of design, construction, and regulatory practices are proposed. The recommendations are based on a combination of hard data, general observations, technical knowledge, and experience. Where data gaps exist, some engineering judgement has been necessary.

The results indicate that a soil barrier alone should not be used within a landfill cover system where site-specific public health and/ or environmental risk factors, or landfill hydraulics, dictate the need for a system with a hydraulic performance equal to or better than 1×10^{-6} cm/sec. Based on the results, we believe that most cover system barrier soils will eventually degrade to a hydraulic performance in the range of 1×10^{-5} cm/sec where they will remain. This realization should be considered when selecting a landfill cover system or investigating closed landfills.

Introduction

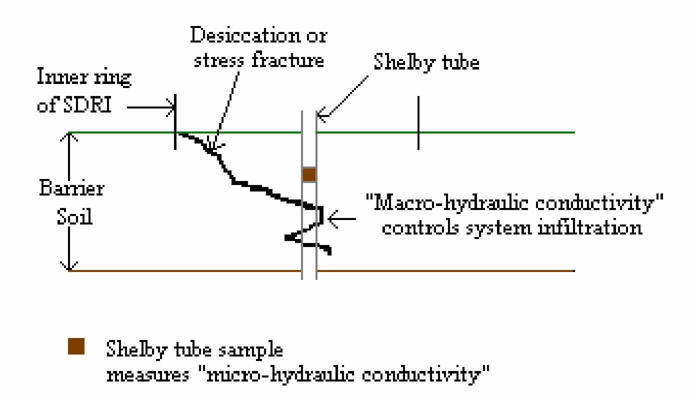
This paper provides a summary of the SDRI test procedures and a brief introduction to the four sites. Detailed information can be found in previously published individual site reports which are referenced throughout this paper. Probable causes of soil degradation and recommendations for changes to the state of practice are detailed. Some discussions regarding the future of landfill final cover system design and a comparison of the differences between large scale and small scale in-situ testing procedures are included.

SDRI Test and Installation Procedures

The SDRI test provides a direct measurement of the infiltration rate through fine grained soils (hydraulic conductivities less than 1 x 10^{-5} cm/sec). The coefficient of hydraulic conductivity can be calculated by knowing the steady state infiltration rate, the depth of water in the outer ring (hydraulic head), and the depth of the wetting front. The depth of the wetting front is determined by developing before and after water content profiles or by other methods such as installing tensiometers.

The SDRI was selected due to its ability to measure infiltration through large defects, which we believe to be the features most likely to control the hydraulic performance of a barrier layer (see Figure 1 below). The preferential flow path (desiccation or stress fracture) depicted on the Figure represents the defect controlling water movement through the barrier soil in this hypothetical cover scenario. It is fully represented within the inner ring of the SDRI but is not picked up by the Shelby tube sample cut in the laboratory.

Figure 1: Preferential Flow Path



The apparatus consists of an open outer 'ring' (7.7 by 7.7 foot square) and a sealed inner 'ring' (4.0 by 4.0 foot square). Our apparatus is of aluminum construction and was fabricated by W.A. Messer, Inc. of Westbrook, Maine in 1993. Typical schematic diagrams (cross-section and plan view) of the SDRI apparatus are depicted in Figures 2 and 3.

Figure 2: Sealed Double-Ring Infiltrometer (cross-sectional view)

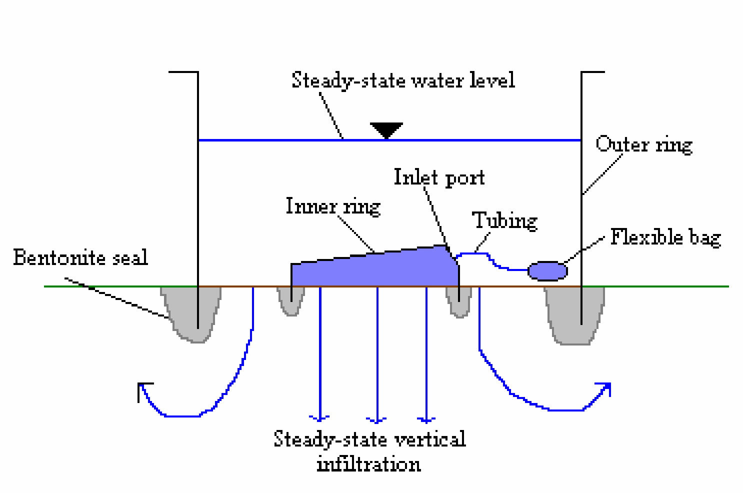
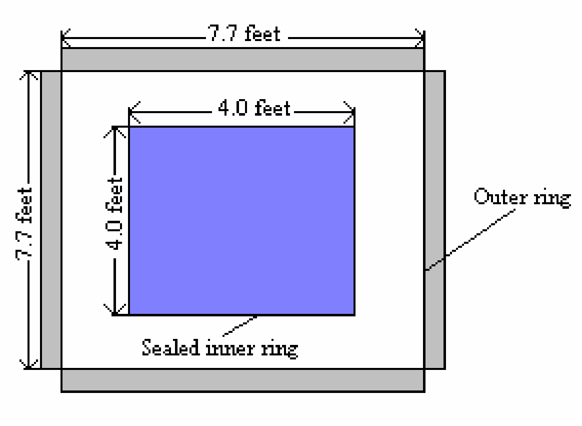


Figure 3: Sealed Double-Ring Infiltrometer (plan view)



Prior to selecting the test location, we visited each site to observe conditions such as slope, topsoil thickness, observable settlement, and vegetative growth. All available construction information was then accumulated and evaluated. The test areas were initially stripped of topsoil and trenches excavated into the barrier soil, either by trenching machine or hand excavation, for the inner and outer rings. The inner ring is typically placed in a trench approximately 0.5 feet deep and the outer ring in a trench approximately 1.0 feet deep, but depths of trenches vary due to slope. Both rings are placed level and sealed into their respective trenches with a mixture of granular bentonite, bentonite chips, and water. The inner ring is filled completely with water and the outer ring is filled to a ponded depth of approximately 1.5 feet above the barrier soil surface. Water is periodically added to the outer ring in order to maintain a reasonably constant depth. The top of the outer ring is covered and insulated to limit evaporation and temperature fluctuations.

The infiltration rate is measured by connecting a flexible bag with a known weight of water to a port on the inner ring. As a volume of water leaves the inner ring and flows into the barrier soil, it is replaced by an equal volume of water from the flexible bag. After a known period of time, the bag is removed and weighed. The volume of water that escaped the bag is then computed. Knowing the volume of water, the surface area beneath the inner ring, and the elapsed time of the test, the infiltration rate can be calculated by the following equation:

(Eq. 1) $I = Q/(At)$

I = rate of infiltration (cm/sec)
Q = flow quantity (cc)
A = area of inner ring (cm^2)
t = time interval (sec)

Once a steady-state infiltration rate is reached, the coefficient of hydraulic conductivity (K) can be calculated using the following relation:

(Eq. 2) $K = I/i$

K = coefficient of hydraulic conductivity (cm/sec)
I = rate of infiltration (cm/sec)
i = hydraulic gradient (ft/ft)

where:

(Eq. 3) $i = (H + D + H_S)/D$

i = hydraulic gradient (ft/ft)
H = depth of water in outer ring (ft)
D = depth to wetting front (ft)
*H_S = suction head at wetting front (ft)

*H_S is assumed to be zero (Trautwein 1989)

Calculated hydraulic conductivities at each of the four sites are presented and discussed later in this paper.

CUMBERLAND

Site Description

The Cumberland Municipal Solid Waste Landfill is located on the south side of Drowne Road near Cumberland Center, Maine. Closure of the five acre landfill was completed in 1992. The final cover system design (from top to bottom) consists of 0.5 feet of vegetative cover and 1.5 feet of compacted marine silty clay. A gas collection system, consisting of 1.5 by 1.5 foot sand trenches with 0.33 foot diameter perforated PVC collection pipes and a series of risers, underlies the cover system. The top area of the landfill (two distinct peaks) is graded at a slope of approximately 5 to 10 percent and the sideslopes are graded at approximately 33 percent. Elevations at the landfill range from 80 feet at the base to 130 feet at the crest.

Laboratory Testing

Laboratory testing of the Cumberland barrier layer was conducted during the 1992 landfill closure (Squaw Bay 1992) and during SDRI tests in 1994 (Haley & Aldrich 1995) and 1998 (MDEP 1999). Additionally, water content profiling was performed in 1996 (Haley & Aldrich 1996). Laboratory test data includes water content versus depth (ASTM D 2216-92), Atterberg limits (ASTM D 4318-93), total unit weight (no standard), and constant head hydraulic conductivity using a flexible wall permeameter (ASTM D 5084-90).

In-situ Testing

In-situ testing was conducted at the time of the landfill closure in 1992 (Squaw Bay 1992) and during SDRI tests in 1994 (Haley & Aldrich 1995) and 1998 (MDEP 1999). In-situ test data includes field moisture-density (ASTM D 3017-88 & 2922-91) and two SDRI tests (ASTM D 5093-90).

Barrier Soil Condition at SDRI Test Sites

Prior to the 1994 SDRI installation, three test holes were excavated to assess the barrier soil condition. It was noted that the exposed surface of the barrier soil was generally moist, dense, and appeared uniformly compacted with no visible surface cracking. Root penetration extended up to 0.4 feet into the barrier soil.

The 1998 barrier soil condition was assessed during hand excavation of the inner and outer ring trenches, observing the barrier soil surface within the inner ring area, and observing the barrier soil surrounding the Shelby tube sample holes after tube retrieval. The surface of the soil was generally moist and appeared uniformly compacted with no visible surface cracking. No fracturing or desiccation was noted within the soil profile. Root penetration, generally to a depth of 0.3 to 0.7 feet, was noted throughout the excavation area. A sand lens was noted at a depth of 0.3 feet in sample hole C98C. One stone approximately 0.2 feet in size was found. No additional stones were noted. These observations are similar to observations made during the 1994 testing.

VASSALBORO

Site Description

The Vassalboro Municipal Solid Waste Landfill is located on the south side of the Lombard Dam Road in Vassalboro, Maine. Closure of the four acre landfill was completed in the Fall of 1990. The final cover system design (from top to bottom) consists of 0.5 feet of vegetative cover (sludge amended topsoil), 1.5 feet of compacted glacial till, and a granular soil gas transmission layer. The top area of the landfill is graded at approximately 3 percent with lengthy side slopes (approximately 33 percent) to the north and west. Elevations at the landfill range from approximately 82 feet at the base to 140 at the crest.

Laboratory Testing

Laboratory testing of the Vassalboro barrier layer was conducted during the 1990 landfill closure (CES 1990) and during SDRI tests in 1994 (MDEP 1995) and 1997 (MDEP 1998). Additionally, water content profiling was performed in 1996 (Haley & Aldrich 1996). Laboratory test data includes water content versus depth, total unit weight, hydraulic conductivity, and one grain size distribution (ASTM D 422-63).

In-Situ Testing

In-situ testing was conducted at the time of the landfill closure in 1990 (CES 1990) and during SDRI tests in 1994 (MDEP 1995) and 1997 (MDEP 1998). In-situ test data includes field moisture-density and two SDRI tests.

Barrier Soil Cover Condition at SDRI Test Sites

Prior to the 1994 SDRI installation, three test holes were excavated by hand to assess the barrier soil cover condition. The test holes exhibited variable thickness' of silty clay loam with small stones and some sand lenses. Stone size varied and was generally less than 0.1 feet although one 0.7 foot stone was removed during excavation of the outer ring trench. The barrier soil was generally moist and slightly desiccated. No root penetration into the barrier soil was noted in the excavations.

The 1997 barrier soil condition was assessed while hand excavating the inner and outer ring trenches and observing the barrier soil surface within the inner ring area. The surface of the barrier soil was dry and moisture appeared to increase with depth. No surface cracking or desiccation was noted. A few small stones (generally less than 0.1 to 0.2 feet) and one 0.7 foot stone was found. Root penetration, generally to a depth of 0.3 to 0.5 feet, was noted throughout the excavation area.

YARMOUTH

Site Description

The Yarmouth Municipal Solid Waste Landfill is located on the East Side of Old County Road in Yarmouth, Maine. Closure of the six acre landfill was completed during 1990. The cover system design (from top to bottom) consists of 0.5 feet of vegetative cover (sludge amended topsoil), 1.5 feet of compacted marine silty clay, and a granular soil gas transmission layer. The top of the landfill is graded to a slope of approximately 5 to 10 percent and the sideslopes graded to a slope of approximately 33 percent. Surface elevations at the landfill range from 30 feet at the lowest point to 105 feet at the peak.

Laboratory Testing

Laboratory testing of the Yarmouth barrier layer was conducted at the time of closure during 1990 (Shaw Brothers 1990) and during SDRI tests in 1994 (Haley & Aldrich 1995) and 1996 (Haley & Aldrich 1996). Laboratory test data includes moisture-density, gradation analyses, hydraulic conductivity, water content versus depth, Atterberg limits, and total unit weight.

In-Situ Testing

In-situ testing was conducted at the time of the landfill closure during 1990 (Shaw Brothers 1990) and during SDRI tests in 1994 (Haley & Aldrich 1995) and 1996 (Haley & Aldrich 1996). In-situ test data includes field moisture-density and two SDRI tests.

Barrier Soil Cover Condition at SDRI Test Sites

Prior to the 1994 SDRI testing, three test holes were excavated by shovel and hand auger in the vicinity of the test set-up. It was noted that the barrier soil was generally moist, dense, and appeared uniformly compacted with no visible cracking. Root penetration extended up to 0.5 feet into the barrier soil. It was noted that the vegetative layer, in the area tested, was only 0.1 to 0.2 feet in thickness.

Prior to installation of the 1996 SDRI, three test holes were excavated by hand to evaluate the barrier soil cover condition. In the area tested, the vegetative layer was approximately 0.3 feet in thickness and the vegetative growth was in excellent condition. The barrier soil was relatively moist with some small stones. Slight cracking of the barrier soil in the upper few inches and a few fine roots to 0.3 feet were noted.

WALDOBORO

Site Description

The Waldoboro Municipal Solid Waste Landfill is located on the north side of the Nobleboro Road in Waldoboro, Maine. Closure of the four acre landfill was completed during the Fall of 1991. The final cover system design (from top to bottom) consists of 0.5 feet of vegetative cover (sludge amended topsoil), 1.5 feet of compacted marine silty clay, and a granular soil gas transmission layer. The top area of the landfill is graded at approximately 5 percent with side slopes of approximately 33 percent. Surface elevations of the landfill range from approximately 200 feet at its low point to 260 feet at its high point.

Laboratory Testing

Laboratory testing of the Waldoboro barrier layer was conducted at the time of the 1991 landfill closure (Kimball Chase 1991) and during SDRI tests in 1993 (Haley & Aldrich 1993) and 1996 (Haley & Aldrich 1996). Additionally, water content profiling was performed in 1994 (Haley & Aldrich 1995). Laboratory test data includes water content versus depth, Atterberg limits, partial washed sieve particle size, Standard Proctor (ASTM D 698-91), total unit weight, and hydraulic conductivity.

In-Situ Testing

In-situ testing was conducted at the time of landfill closure in 1991 (Kimball Chase 1991) and during SDRI tests in 1993 (Haley & Aldrich 1993) and 1996 (Haley & Aldrich 1996). In-situ data includes field moisture-density and two SDRI tests.

Barrier Soil Cover Condition at SDRI Test Sites

Two test holes were excavated in the vicinity of the 1993 SDRI test set-ups by shovel and hand auger. The barrier soil was generally dry, dense, and appeared uniformly compacted. It appeared drier and more brittle near the upper portions and moderately moist and plastic near the bottom. Significant surface cracking and desiccation was observed at various locations within the SDRI test sites (Weaver et al. 1994). It was noted that the thin-walled tube soil samples showed significant desiccation. The upper 0.5 to 0.7 feet of the barrier soil was dry and severely desiccated with evidence of root penetration (Weaver et al. 1994).

During 1996, the barrier soil cover condition was assessed while excavating the inner and outer ring trenches. The barrier soil was generally dry and crumbly with severe desiccation noted throughout the entire area of trench excavation, although the severity tended to decrease with depth. Soil excavated from the trenches was dry and brittle, crumbling into small, blocky clods (Figures 4 and 5). A few small stones (generally less than 0.2 to 0.3 feet) were found. Significant root penetration, generally to a depth of 0.3 to 0.4 feet, was noted throughout the excavation area (Figure 4).

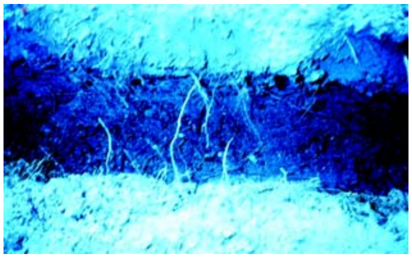


Figure 4

Root penetration and blocky clods within the Waldoboro barrier soil.

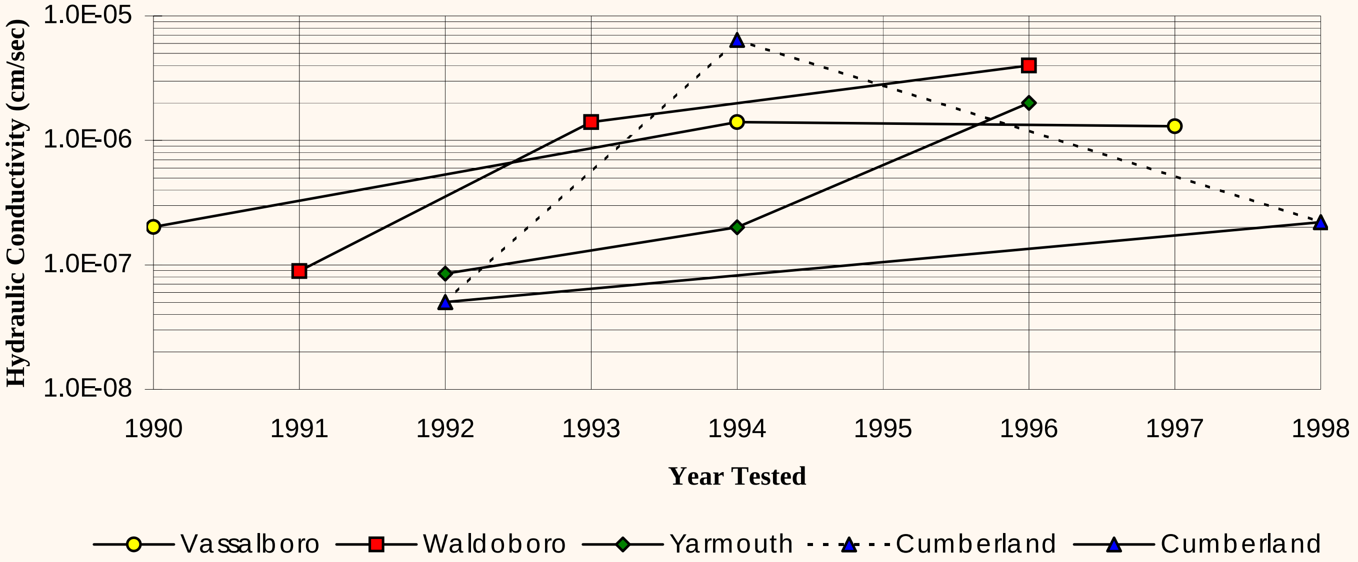
Figure 5

Blocky clods within the Waldoboro barrier soil.

Results

The results of our evaluation clearly demonstrate that all four soil barriers have been undergoing degradation, with an associated loss of hydraulic properties. Figure 6, Final Cover System Hydraulic Conductivity Increase graphically depicts the loss of hydraulic performance found at each of the four landfills. The apparent barrier soil hydraulic conductivity increase at the four sites ranges from six fold (Yarmouth) to forty fold (Waldoboro). We note that the results from the 1994 testing at Cumberland should be viewed as perhaps not representative of average in-situ conditions for reasons discussed with the presentation of the Cumberland results later in this paper.

Figure 6, Final Cover System Hydraulic Conductivity Increase



Based on Figure 6, we believe that the four soil barriers will eventually reach a steady-state hydraulic conductivity on the order of 1 x 10^{-5} cm/sec. These values are approximately two orders of magnitude greater than the as-built conditions. An exception may be for the glacial till barrier at Vassalboro, which appears to have reached a static hydraulic conductivity of approximately 1 x 10^{-6} cm/sec. Possible reasons for the difference at Vassalboro will be provided in subsequent sections.

The data clearly show that there is a consistent correlation between drying, observed large scale fracturing and desiccation, increased infiltration rates, and possibly the Plasticity Index (PI) of the soil. A brief summary of the individual sites follows. More detailed information can be found in the individual site reports previously referenced.

Cumberland

The 1994 SDRI test indicated an increase in hydraulic conductivity from the time of construction in 1992 of about 100 fold while the 1998 test indicated a six fold increase. The 1994 Cumberland SDRI test location was underlain by a gas collection trench. The gas movement or migration below and upwards through the barrier soil, and differential settlement around the trench, were significant contributors to barrier soil cracking and the subsequent hydraulic conductivity increase at the test site. Although the 1994 SDRI determined hydraulic conductivity may be representative of areas with an underlying gas collection trench, or other areas of settlement, the barrier soil in general appears to have retained more of its initial hydraulic properties. This is evidenced both by the follow-up water content profiling conducted in 1996 and the 1998 SDRI test.

Based on 1996 and 1998 test data and other observations, we conclude that a combination of several factors have contributed to a relatively longer-term maintenance of the Cumberland soil barrier's hydraulic properties (Figure 6). Some of the factors include: an optimal topsoil, seeding, and fertilizer mix; the lack of drying within the barrier soil; a quick establishment of vegetative cover; and sound barrier soil construction and construction quality assurance techniques. It is our belief, however, that the mechanisms which have driven the hydraulic degradation seen at other sites will eventually control at Cumberland resulting in a similar magnitude of increase in hydraulic conductivity.

Vassalboro

Between the time of its installation in 1990 and the 1994 SDRI test, the Vassalboro barrier soil underwent an apparent increase in hydraulic conductivity of about ten fold. The 1997 SDRI test showed similar results to the 1994 test, indicating that no hydraulic degradation had occurred since 1994. We believe that the Vassalboro barrier soil has reached a static hydraulic condition (one that will not further change with increasing years in service).

Yarmouth

Between the time of its installation in 1990 and the 1996 SDRI test, the Yarmouth barrier soil underwent an apparent increase in hydraulic conductivity of about thirty fold. Between 1990 and 1994, the soil barrier showed only a relatively small increase in hydraulic conductivity. Significant degradation occurred between 1994 and 1996 and will most likely continue until it reaches a static condition. Some possible reasons for the delayed degradation at Yarmouth include good construction techniques and an early grass catch, which resulted in good vegetative coverage.

Waldoboro

The hydraulic conductivity of the Waldoboro barrier soil has apparently increased about forty fold since its installation in 1991. Two SDRI tests completed during 1993 showed an increase of about twelve fold up to that time. A subsequent increase of two and a half fold occurred between 1993 and 1996. It is clear that hydraulic degradation of the Waldoboro barrier is ongoing, although at a slower rate, and will most likely reach a static hydraulic conductivity on the order of 1×10^{-5} cm/sec. Some factors probably contributing to the more rapid degradation at Waldoboro include drying, root penetration, and poor establishment of vegetation.

Causes of Hydraulic Degradation

We believe that several factors have played a role in the degradation found at each of the testing sites. Of the factors discussed below, drying trends appear to be the most important contributor to marine silty clay hydraulic degradation. Freeze-thaw phenomena, root penetration, settlement, quickness and quality of vegetative establishment, and gas movement may also play a part in the degradation process.

- To look at the drying relationship, we obtained precipitation data from weather stations located near each of the test sites. We then compared the precipitation records with water content data obtained from laboratory testing of barrier soil samples taken adjacent to the test sites. As a result of our comparison of the precipitation and water content data, and subsequent visual observation of desiccation and fracturing of the soil barriers, it appears reasonable to conclude that two different drying mechanisms have occurred.

First, there is a seasonal fluctuation in water content, the result of precipitation events and evapotranspiration conditions, that is recognized in all natural surficial soils. This can be thought of as the soil being at a moisture equilibrium for its position in the surrounding environment. Second, is a long-term trend toward a drier state, most likely resulting from the barrier soils being placed at a water content above the natural static or equilibrium condition for the depth and topographic setting (its hydrologic setting) they are placed at within the final cover system. Typically, soil barrier material is excavated from a borrow pit, transported to the site, moisture conditioned, and compacted at a water content above optimum. In their new location the barrier soils are not influenced by a seasonal high ground water table and are well within the zone impacted by evapotranspiration. Because of these factors, the barrier soil will tend to seek a lower static moisture condition reflecting equilibrium conditions for its new hydrologic position in the environment (final cover system). This static moisture condition is probably several percentage points lower than the above optimum water content at which the barrier soil was placed.

As plastic soil such as clay dries it loses pore water. This pore water loss results in shrinkage of the soil mass and, subsequently, cracking and desiccation as the attractive forces within the clay cause individual clods to form. Upon rewetting the soil tends to swell, however the preferential pathways still exist and result in an increased barrier soil hydraulic conductivity. Drying and shrinkage trends, clearly not related to seasonal fluctuations, are evident, to different extents, in the marine silty clay barriers at Cumberland, Waldoboro, and Yarmouth. These trends are occurring from the top of the barrier soil downward. No such trend is evident in the glacial till barrier at Vassalboro.

- The relationship between drying trends, desiccation and cracking, and hydraulic degradation is especially clear at the Waldoboro site, where the most extensive study to date has taken place. The glacial till barrier at Vassalboro, on the other hand, has shown no general drying trend. The water content has been generally consistent with depth and correlates almost directly with seasonal precipitation. While hydraulic degradation has been measured at Vassalboro, it appears to be less severe than at the marine silty clay sites. We believe that it is attributable to other causes, such as freeze-thaw cycles. Based on recent test data, we believe that the Vassalboro barrier soil has reached a static hydraulic conductivity (one that will not further degrade). The other sites will also reach a static hydraulic conductivity, but apparently one that is substantially higher than at Vassalboro.

- There may be a relationship between general drying trends, the amount of barrier desiccation, the rate and degree of hydraulic degradation, and the plasticity index (PI) of a soil. The PI provides a measure of the cohesiveness of a soil and is defined as the liquid limit (LL) minus the plastic limit (PL). If the apparent relationship holds, the barrier soil with the lowest PI should have the lowest degree of hydraulic degradation over time. Likewise, higher PI soils should have more degradation over time. The data supports this theory in a general sense. Although this connection is preliminary, it appears to indicate that selecting or specifying a barrier soil with a lower PI may lessen the eventual reduction in hydraulic performance. This apparent relationship is probably due to the lower natural water content of soils with a lower PI.

- Freezing and thawing of barrier soils may cause a general increase in hydraulic conductivity and has long been considered one of the primary factors in hydraulic degradation. We believe that, while freeze-thaw cycles are a contributor to degradation, they are not as significant as the general drying trends, at least when considering marine silty clay soil barriers. Freeze-thaw appears to contribute to an increase in void ratio within a barrier soil. As a block or unit of soil freezes, the water contained within the soil matrix expands. As thawing occurs, the soil matrix is 'loosened' as the water compresses to its original volume. The resulting increase in void ratio is probably a less substantial contributor to hydraulic degradation of cohesive soils than the large scale desiccation and fracturing which results from overall drying trends. It is likely that the degradation seen in the more cohesionless glacial till soil barrier at Vassalboro is primarily the result of freeze-thaw cycles.

- Root penetration into, or in proximity to, a barrier soil may cause hydraulic degradation through drying as the roots remove water needed for plant growth. Cracking of the soil due to root channeling in the barrier will also occur. We observed significant root growth into the top 0.4 feet of the Waldoboro barrier soil (Figures 4 and 5). Root penetration was also evident in the Cumberland, Vassalboro, and Yarmouth soil barriers.

- Differential or global settlement of a barrier soil will cause cracking and a subsequent decrease in hydraulic performance. We suspect that settlement caused by an underlying gas trench contributed to the significant increase in hydraulic conductivity found in the Cumberland barrier soil during the 1994 testing. Settlement is not believed to be a significant contributor to the degradation found at any of the other sites.

- The lack of early vegetative establishment, and/ or the eventual development of poor vegetative growth, appears to lead to more rapid drying and degradation when compared to sites where good, early vegetative growth is established. A good stand of vegetation appears to help maintain the moisture condition of a barrier soil, at least initially. A comparison of Waldoboro, where the vegetation took several months to become established and eventually resulted in a fair to poor growth, with Yarmouth, where vegetation was immediately established by hydroseeding and is in excellent condition, provides a good example of the role of vegetation in delaying hydraulic degradation. A healthy vegetative layer may also provide some insulation against frost penetration.

- Gas movement or migration below and upward through a barrier soil may cause drying of the layer. We have seen some evidence of this occurring at the Cumberland site where the soil water content distribution shows a slight drying of the barrier in the lower 0.3 feet. Field observations also indicate that the clay appeared visually drier at the bottom. As noted previously, the 1994 SDRI test location at Cumberland was directly underlain by a gas collection trench. There was no evidence of drying of the barrier soil due to gas movement at any of the other tested sites.

Changes to the State of Practice

We are recommending some changes to the current state of practice based on our studies of in-service landfill final cover system soil barriers. The 'state of practice' is meant to encompass design, construction, maintenance, and regulatory measures, all of which are interrelated. The recommendations presented below are based on a combination of hard data, general observations, experience, and industry knowledge. It is important to note that these recommendations are generally intended to pertain to sole soil barriers in final cover systems and not to composite barriers or landfill liner systems. Soil barriers in those systems are subject to entirely different moisture dynamics.

1. A soil barrier alone should not be used within a landfill final cover system where site-specific public health and/ or environmental risk factors, or landfill hydraulics, indicate the need for a final cover system with a hydraulic performance equal to or better than 1×10^{-6} cm/sec. For planning purposes, it should be assumed that a single marine silty clay barrier will eventually reach a steady-state hydraulic conductivity on the order of 1×10^{-5} cm/sec.

2. Consideration should be given to placing a cover system soil barrier at a lower water content (below optimum) in order to limit the amount of degradation that seems to occur as a result of drying. The initial hydraulic conductivity should still be achieved while implementing this recommendation.

3. Designers, contractors, and regulatory agencies should place an emphasis on requiring, specifying, and locating glacial till, or other low PI clay material, as an alternative to the current preference which is focused on plastic marine silty clays.

4. Public and private concerns alike should continue and intensify efforts to develop and utilize alternatives to barrier soil, used as the sole barrier, within landfill final cover systems.

5. Protective cover material (capillary breaks) or thicker overburden layers should be given increased consideration where sole soil barrier layers are specified within a landfill final cover system.

6. Efforts should be made to determine the optimal topsoil, seeding, and fertilizer mixes and methods. Objectives should be to provide a successful early establishment of vegetation with good ground coverage and minimal root depth.

7. A gas generation and management assessment should be completed prior to designing a barrier system. The design should seek to efficiently remove and vent landfill gases while minimizing contact with the soil barrier.

8. All landfills should be evaluated for settlement potential prior to designing a final cover system. If necessary, reinforcement should be provided within the cover system.

9. Specifications should require the use of kneading compaction with equipment which fully penetrates the entire lift thickness in order to remold the soil and break up clods.

10. Test pads should be required for all installations and used to verify that the material, equipment, and methods of compaction are able to remold the soil and bond all lift interfaces.

Future of Final Cover System Design

Composite Systems and Alternative Barriers

Our studies have focused on the testing of soil cover systems at older, unlined municipal landfills. At newer, lined (secure) landfills, soil cover systems are being replaced by composite systems. That is, systems with two or more barrier components adjacent to each other providing a synergistic effect. For example, a composite final cover system could consist of a geomembrane and a soil barrier or a geomembrane, geosynthetic clay liner (GCL), and a soil barrier. These systems have been shown to be more impermeable than soil systems over the long-term and will continue to be emphasized in the future.

Just as composite systems are replacing soil systems, alternative barriers, such as sludge or bentonite amended soils, may replace soil components within composite and single barriers alike. Alternative barriers should continue to receive consideration in the future. Single geosynthetic barriers, such as GCL’s or geomembranes, may be substituted for soil barriers in some instances.

In-Service Cover Systems

Although final cover systems with fine grained soils used as the sole barrier layer are generally being phased out over time and replaced with composite or alternative systems, the remediation of in-service cover systems will remain an issue over the long-term. Periodic inspections of these in-service systems should be conducted in order to evaluate their long-term performance. Poor hydraulic performance of the barrier soil will likely be the primary factor contributing to the need for system remediation. High waste moisture content, poor landfill siting, or a high groundwater table may also contribute.

Presently, the Department, through the Closure and Remediation program, is involved with four active landfill remediation projects. Several other landfills have been identified as potential remediation projects. Remedial techniques may include improving the in-service condition of landfill final cover systems, replacing or improving existing community water supply systems, or implementing institutional controls.

Large Scale Versus Small Scale Testing

During the testing program, the Department has had the opportunity to evaluate large scale (SDRI) versus small scale (thin walled tube samples) hydraulic testing. Along with each SDRI test, a thin walled tube (Shelby) soil sample was retrieved at each of the test sites for comparative laboratory testing. Generally, we have found that the SDRI test is in very close agreement with the laboratory flexible wall permeameter test when measuring the bulk hydraulic conductivity, where large scale desiccation or fracturing has not occurred. On the other hand, where desiccation and fracturing exist, the SDRI has consistently determined a significantly higher hydraulic conductivity. Assuming that homogenous barriers are constructed, we believe that the laboratory testing of Shelby tube samples provides a valid indication of hydraulic conductivity for construction quality assurance purposes. Construction techniques and quality assurance procedures to assure homogenous soil barrier layer construction are well established. We do not believe that Shelby tube samples will provide reliable data for assessing the performance of in-service soil barriers where large scale desiccation or fracturing has occurred.

SDRI testing should be considered as an alternate method of hydraulic conductivity measurement on test pads. The results, if meeting the specifications, could be used to reduce or eliminate in-place hydraulic conductivity testing during full scale barrier soil placement. Time constraints may, however, limit the opportunity to take advantage of the SDRI test as part of a construction project. Based on the nine tests completed during our study we estimate that it will take between twenty and sixty days to achieve a steady-state infiltration rate within soil barrier layers. Unquestionably, SDRI testing, in lieu of laboratory small scale testing, should be used to assess the hydraulic condition of in-service fine grained soils used as the sole barrier layer in final cover systems.

Conclusions

The data accumulated to date clearly demonstrate that all four barriers have undergone hydraulic degradation over time. The SDRI derived hydraulic conductivities at the four sites have increased between six and forty fold during service lives ranging from four to seven years. Based on analysis of the data and other observations, we believe that the three marine silty clay barriers will eventually reach a static (steady-state) hydraulic conductivity on the order of 1×10^{-5} cm/sec, while the glacial till barrier may have already reached a static hydraulic conductivity of about 1×10^{-6} cm/sec. All four barriers were constructed to an initial hydraulic conductivity of about 1×10^{-7} cm/sec. When evaluating the options for final closure of a landfill, it should be recognized that a compacted fine-grained soil, when used as a sole barrier, will most likely undergo the magnitude of hydraulic degradation measured at these facilities over its own service life.

In considering field and laboratory testing data, as well as direct in-situ observation of the barrier layers, it is apparent that the primary factor controlling the degradation of compacted cohesive (silty clay) soils is the general long-term moisture loss and desiccation cracking associated with its hydrologic location in a landfill cover system. The primary factors controlling the degradation of more cohesionless (glacial till) type soils are probably related to other mechanisms, such as freeze-thaw cycles. Settlement, root penetration, and gas migration are also suspected contributors to the loss of hydraulic properties. We have discussed a number of factors which may control the rate of hydraulic degradation.

We have provided several recommendations for changes to the state of practice based on our data and observations. They cover a range of topics including design, construction, maintenance, and regulatory measures, all of which are interrelated. Most of our recommendations describe measures which can be taken to slow, and possibly to some extent to help limit, the degradation process. A primary recommendation, however, is that a soil barrier alone should not be used within a landfill final cover system where site-specific public health and/ or environmental risk factors, or landfill hydraulics, indicate the need for a final cover system with a hydraulic performance equal to or better than 1×10^{-6} cm/sec.

Finally, we have concluded, based on our study and previous experience, that thin-walled tube samples tested in a triaxial flexible wall permeameter apparatus will provide accurate construction quality assurance (CQA) information, provided a homogeneous barrier layer is placed. The thin-walled tube samples, however, will probably fail to detect the large-scale defects which are likely to be the features that control infiltration through in-service barrier layers that have undergone the desiccation and cracking associated with degradation over time. Due to its ability to encompass defects over a sixteen square foot area or larger, the SDRI test is appropriate and recommended for in-service hydraulic evaluations of cover systems.

The contents of this paper are generally intended to relate only to compacted fine-grained soils that are used as the sole barrier layer in a landfill final cover system. Barrier layers used as a component of a composite system, or those used in a landfill liner, are subject to entirely different moisture dynamics and will behave differently.

This study has been funded by the Department’s Landfill Closure and Remediation Program, which is responsible for administering State funds bonded for the final closure and remediation of municipal solid waste landfills. The State of Maine, through the Closure and Remediation Program bond authorization program, has reimbursed millions of dollars annually to municipalities since its inception in 1987. In addition to State efforts, private concerns also have expended, and continue to expend, considerable funds towards the final closure of commercial and industrial landfills.

We are grateful for the assistance of many individuals for their participation in the Department’s SDRI testing program. They include the Landfill Closure and Remediation Program, the Towns of Cumberland, Vassalboro, Waldoboro, and Yarmouth, Haley & Aldrich, Inc., Dames & Moore, and several past and present Department employees.

References

Civil Engineering Services Inc., "Compliance Certification for Closure of a Solid Waste Disposal Facility, Vassalboro Landfill," November 11, 1990.

Haley & Aldrich, Inc., "Report on Hydraulic Conductivity Evaluation of Landfill Cover - Waldoboro, Maine," 25 October 1993.

Haley & Aldrich, Inc., "Laboratory Testing Results for Landfill Cover Systems - Vassalboro and Waldoboro, Maine," 13 February 1995.

Haley & Aldrich, Inc., "Report on Hydraulic Conductivity Evaluation of Landfill Cover - Cumberland and Yarmouth, Maine," 20 June 1995.

Haley & Aldrich, Inc., "Report on Hydraulic Conductivity Evaluation of Landfill Covers," 4 January 1996.

Haley & Aldrich, "Letter Report to the MDEP," July 24, 1996.

Haley & Aldrich, "Letter Report to MDEP," August 6, 1996.

Kimball Chase Company, Inc., "Certification Report, Waldoboro Landfill Closure, Waldoboro, Maine," December 6, 1991.

Maine Department of Environmental Protection, Division of Technical Services, Solid Waste Engineering Unit, "Implementation of a Sealed Double-Ring Infiltrometer to Evaluate The Long-Term Hydraulic Performance of a Barrier Soil Cover - Vassalboro, Maine," March 17, 1995.

Maine Department of Environmental Protection, Division of Technical Services, Solid Waste Engineering Unit, "Follow-up Barrier Soil Performance Testing, Vassalboro Landfill," June 1998.

Maine Department of Environmental Protection, Division of Technical Services, Solid Waste Engineering Unit, "Follow-up Barrier Soil Performance Testing, Cumberland Landfill," March 1999.

Shaw Brothers Construction, Inc., "Letter Report to the Town of Yarmouth," May 22, 1990.

Squaw Bay Corporation, "Town of Cumberland Drowne Road Landfill Closure Final Construction Report," October 1992.

Trautwein, Stephen J., "Field Measurement of Infiltration Rates Using a Sealed Double-Ring Infiltrometer," October 1989.

Weaver, James W., Christopher L. Snow, Stephen E. Farrar, and Karen L. Hefler, "Hydraulic Conductivity Evaluation Of Existing Landfill Cover" prepared for ASCE Technical Symposium, Practical Application of Soil Barrier Technology, February 9, 1994.