Compacted Clay Liners

A Viable Solution for Landfill Leachate Containment

Paper Submitted By:

Matthew R. Cawley
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Dr. Norman Jones
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Brigham Young University
Provo, UT

Abstract

Since the beginning of time, man has created and disposed of waste materials. Unfortunately, with the exception of the past 30 or 40 years, this practice has been carried out with little regard for the environment. While the total volume of waste materials, being an integral part of any society, can be reduced through the use modern technology, they can not be completely eliminated. Waste materials that can not be recycled or eliminated must therefore; be placed in a landfill.

Landfills have always constituted a common method for the disposal of societal waste products. The landfills of the past however, have not performed effectively at containing the waste materials deposited within them. With the detection of environmental problems, stemming from ineffective waste containment, considerable research and development has been devoted to designing effective containment systems for landfill sites.

The United States Environmental Protection Agency (EPA) has specified that compacted clay may be used as an effective barrier for the containment of landfill leachate. Compacted clay liners have proven to be a very effective barrier system. The state of Wisconsin has successfully constructed and employed compacted clay liners for their municipal landfills for the past 20 years. These systems, however, must be designed and constructed with great care. If care and consideration is given to material characteristics, construction techniques, and pre/post construction monitoring, a compacted clay liner can serve and protect a community for many years.

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Feasibility of Compacted Clay Liners

The Wisconsin Department of Natural Resources (WDNR) has required the use of thick clay liners combined with a leachate collection system as a means of groundwater protection at municipal and non-hazardous industrial solid waste landfills for almost 15 years (Gordon et. al., 1990).

Liner Thickness

The Wisconsin Department of Natural Resources (WDNR) who has monitored and operated over 80 clay lined municipal landfills since 1976, requires that their compacted clay liners have a minimum thickness of 1.5 m. A thickness of 1.5 m is required for several reasons. Early experience with clay liner construction in Wisconsin revealed several instances where thinner liners were not adequately constructed leaving little or no barrier at the base of some sites. A liner thickness of 1.5 m is specified so as to provide a “substantial factor of safety.” The factor of safety is required to guard against construction errors and to compensate for the difficulty of grading the large aerial extent, of a liner, to close tolerances (Gordon et. al., 1990).

The state of Wisconsin also requires that liner efficiency modeling be performed to optimize leachate collection efficiency as well as to help predict the amount of leachate which will require treatment (Gordon). The state uses a model, developed by Wong (1977), which assumes the existence of a uniform liner and does not account for construction variability. With the use of the Wong model, the analysis showed that even with a uniform construction assumed, a linear thickness of less than 0.6 m would result in a sharp increase of leakage through the liner (Kmet et. al., 1981). As the liner thickness is increased, the flow through the liner is significantly decreased. The trend of decreasing flow is observed until a thickness of 1.2 m to 1.8 m is reached. At this thickness, the decrease in flow is minimal compared to the increase in thickness (Gordon et. al., 1990).

The United States Environmental Protection Agency (EPA) has a minimum thickness requirement of greater than or equal to 0.9 m. The effective performance record of the WDNR over the past 20 years proves that a minimum thickness of 1.5 m provides a consistent and effective barrier against leachate transport. While it could be argued that a thickness of 1.5 m is simply over design. The Wong model indicates that the EPA's value of 0.9 m tends to be low. If a single liner system is to be constructed, the EPA's minimum requirements might not be sufficient to restrict leacate transport within desired limits. As such, it is recommended that a minimum liner thickness of 1.2 m to 1.8 m be used to provide an effective flow barrier.

Moisture Content and Density

Moisture content and dry density values can greatly affect a soil's ability to restrict the transmission of flow. Generally, placement conditions that result in a high dry density and a moisture content wet of the line of optimums lead to the lowest values of hydraulic conductivity (Mitchell et. al., 1990).

The ideal moisture content and dry unit weight can be determined by running a series of Proctor Compaction Tests on the desired soil type. By performing Modified, Standard and Reduced Proctor Tests and plotting the results on a Moisture Content vs. Dry Unit Weight graph, the Line of Optimums can be identified and plotted. The Zero Air Voids Curve should also be plotted on this graph. With the line of optimums as the bottom boundary and the zero air voids curve as the top limit, the acceptable zone of values may be defined.

An example of a completed Moisture Content vs. Dry Unit Weight graph is provided below. As previously stated, the acceptable zone is bounded between the Line of Optimums and the Zero Air Voids Curve. The zone of values bounded by these two curves satisfies the previously stated condition, that the lowest values of hydraulic conductivity occur when; the dry unit weight is high and the moisture content is on the wet side of optimum.

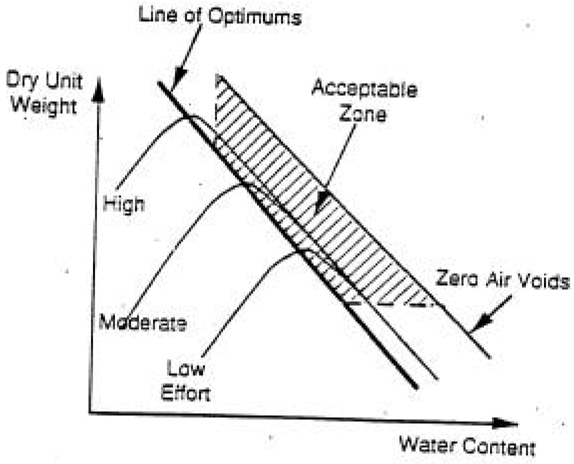

Figure 1: Determination of acceptable Dry Unit Weight and Moisture Content parameters

The Acceptable Zone provides a range of paired Dry Unit Weight and Moisture Content values that will result in low values of hydraulic conductivity when effective and proper compaction is achieved.

Liner Lifts and Compaction

Several types of compaction devices are available for construction purposes. For compacted clay liners however, a heavy compactor with footed roller, such as a “sheep’s foot” roller, is the best option. The weight of the roller is essential as sufficient weight must be provided to ensure that adequate compactive energy is delivered to the soil.

David E. Daniel suggests that minimum compactor weights of 18,000 kg for horizontal surfaces and 14,000 kg for sloped surfaces be used as a guide (Daniel, 1990).

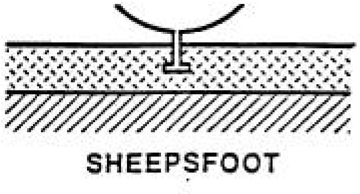

Figure 2: Sheep's Foot Roller

Kneading compactors such as the sheep’s foot roller are ideal for the construction of clay liners. The natural kneading action of the roller feet result in large shear strains within the soil structure. Shear shear strains cause realignment on the molecular level of the clay structure. The realignment yields a dispersed structure, which holds many beneficial qualities with respect to a compacted soil liner. Through assuming a dispersed structure, the clay layer is able to obtain lower hydraulic conductivity values than could be obtained at a similar density with static compaction.

The figure below illustrates the structural differences between a dispersed structure and a non-dispersed structure. The dispersed soil fabric (a) consists of clay particles, which are oriented in a parallel packing scheme. The parallel orientation of the soil particles result in fewer void spaces available for fluid flow. In addition, the voids in a dispersed structure are typically much smaller than voids in a non-dispersed structure. By decreasing the average pore size, head loss values increase and the energy required to transmit flow through the layer also increases. These changes result in a significantly reduced value of hydraulic conductivity.

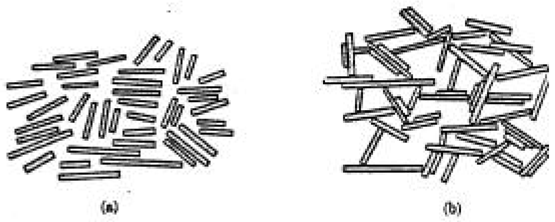

Figure 3: Dispersed Structure vs. Non-Dispersed Structure.

As the liner is constructed, the depth of each lift must not exceed the length of the roller foot. The feet must fully-penetrate each lift to insure that shear strains distributed throughout the entire layer. Only through full penetration is proper compaction achieved. WDNR has set a maximum thickness limit of 15.26 mm for all landfill liner construction projects in Wisconsin (Gordon et. al., 1990). This thickness requirement recognizes two distinct goals. First, by specifying such a thin depth per lift, full penetration by the roller feet is assured. Second, the thin layer is a safeguard against a truckload of marginal having a large effect on the performance of the liner (Gordon).

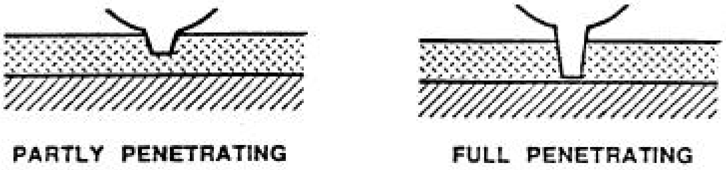

Figure 4: Full vs. Partial Penetration of the Sheep's Foot Roller Foot.

When using a footed compactor, it is important to make a number of passes over the entire area needing compaction. Sheep's foot rollers compact from the bottom up. As multiple passes are performed, the compactor will "walk-out" of the clay liner as the layer becomes compacted and penetration depths are decreased. While each soil type and moisture content combination requires a unique number of passes to reach optimum compaction, Daniel suggests that a minimum of 5 passes must be made before adequate compaction can be achieved.

The Soil Fabric

Mitchell and Madsen (1987) stated that there are three primary stages of soil fabric which are of concern when working with fine-grained materials as barriers to the flow of chemicals. These three levels are: the micro-fabric, the mini-fabric and the macro-fabric. The micro-fabric consists of the regular aggregations of the particles and the very small pores within the aggregates through which little fluid will flow. The mini-fabric contains the previous aggregations and the larger inter-assemblage pores through which flows will be much greater than through the intra-aggregate pores, since the hydraulic conductivity varies with the square of the pore radius. The final stage of soil fabric, the macro-fabric, consists of the cracks, fissures, root holes, laminations, etc., through which the flow rate is so great in comparison with the other flows as to largely obscure them (Mitchell et. al., 1990).

Lift Interface

While it is essential to create the clay liner in a series of lifts to achieve optimum compaction, the interface between lifts can result in a thin macro-fabric zone. If precautions are not taken to unify the zone between lifts, large-scale lateral flow may occur between lifts. Lateral transport of leachate along the lift interfaces puts the leachate in communication with any number of vertical mini and macro-fabric zones, which would otherwise be relatively isolated from flow. This system results in high hydraulic conductivity preferential flow paths and rapid transport of the leachate to the substrata. The following figure gives an example of how a fluid will breach a compacted soil liner by searching out preferential flow paths.

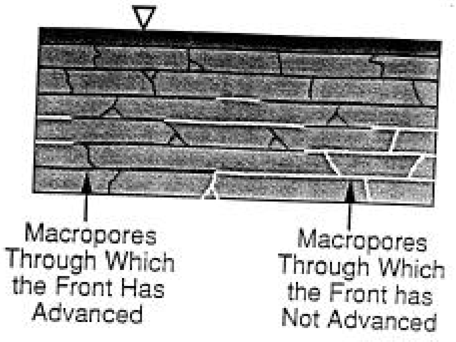

Figure 5: Preferential Flow Paths Due to Poor Adherence between Lift Layers and Vertical Defects.

To limit the potential for lateral flow along the lift face, the exposed surface should be prepared prior to placing an additional lift. Surface preparation is performed by scarifying the exposed surface to a nominal depth of 25 mm prior to placing soil for the next lift (Herrmann and Elsbury, 1987). Scarifying the surface allows two lifts to blend together as the additional lift is compacted. By blending the surfaces between lifts a lower hydraulic conductivity may be achieved within this zone.

Clods Within the Liner Profile

Clods, which are aggregations of soil particles, will also result in higher than predicted values of hydraulic conductivity. Clods are a significant problem as they will introduce both mini-fabric (interior of the clod) and macro-fabric (clod liner interface) zones within the liner. The presence of clods can therefore, significantly increase the hydraulic conductivity of a compacted clay liner. Clods, which commonly occur in cohesive materials, can range in size from very small to very large. The EPA has set standards, which require that all clods larger that 25 mm should be mechanically pulverized previous to compaction.

Stephan J. Truatwein and Charles E. Williams give an account of a test pad, which after being constructed, suffered from higher than anticipated flow rates due to the existence of soil clods. A sealed double ring infiltrometer (SDRI) (see Figure 11) test predicted that the soil to be used (PI = 20 and W(opt.) = 12.5%), would achieve a hydraulic conductivity in the range of $2X10^{-8}$ cm/s. The pad was constructed in four 150 mm lifts. The Quality control during the construction was reported as average. The construction specifications were typical of those used for many landfills, i.e., density equal to or greater than 95% maximum density from a standard proctor test and moisture content at or above optimum. The soil was processed to reduce clod size and particles larger than 25 mm were screened off. Once the pad was completed an infiltration test was performed using an SDRI. The average hydraulic conductivity after a test period of 40 days was $6X10^{-7}$ cm/s, a value which was 30 times the value predicted by the laboratory test.

A trench was excavated through the test pad and the sides of the trench were examined. Although the soil was well compacted, clod interfaces could be seen and poor bonding at lift interfaces was observed.

The effect of clods on hydraulic conductivity is further illustrated by Daniel (1984): the hydraulic conductivity of a compacted clay increased from 9 X 10-9 cm/s to 3 X 10-7 cm/s for an increase in average clod size from 1.5 mm to 9.4 mm.

To minimize the increase in hydraulic conductivity due to the existence of clods, the soil should be prepared prior to compaction. Several techniques are commonly used to reduce the size of clods within the soil. Some of the more common pre-compaction methods include: running the soil through a road-reclaiming machine, using a tractor and disk combination on the soil and blading the soil with a bulldozer.

Destruction of clay clods is also possible during compaction. The following methods are suggested by Benson and Daniel (1990): (1) by compacting the soil at a high molding water content so that the clods are made soft and weak, and can be easily crushed during compaction (provided the soil is reasonably workable at high water content); (2) or by compacting the soil at a lower water content but with and extremely heavy roller that crushes the clods. The following graphs illustrate the relation, which exists between clod size and hydraulic conductivity.

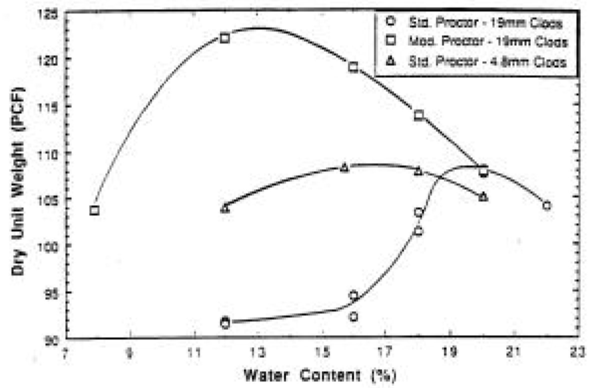

FIG. 4. Standard and Modified Proctor Compaction Curves

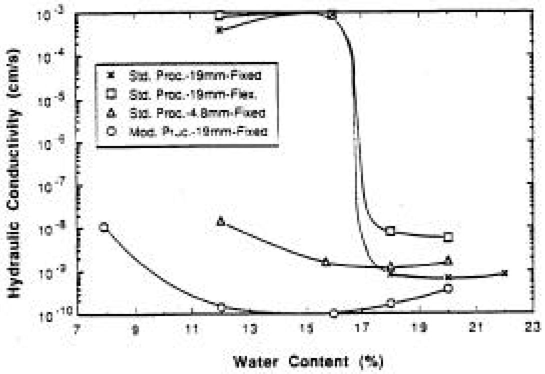

Figure 6: Relationship between Clod Size and Hydraulic Conductivity with Moisture Content.

These graphs show that as the moisture content is increased, clods will moisten and disintegrate. The destruction of the clods result in a greatly reduced value of hydraulic conductivity. As non-homogeneous elements within the soil profile are eliminated, the performance of the liner will be greatly improved.

Desiccation

As a compacted soil liner is constructed it is important to guard against desiccation or the drying of the soil liner. If the soil's moisture content is allowed to decrease significantly, the clay liner will lose its ability to act as an effective barrier against flow.

As moisture is lost, the structure of the soil will change. This change often results in the formation of cracks and fissures throughout the zone of decreased moisture content. While these cracks may be very small in size, they pose a serious problem as; they will become preferential channels for flow. Preferential flow channels within the liner must be avoided, since they significantly increase the hydraulic conductivity and can lead to an eventual piping failure of the compacted soil liner. Even in the absence of a piping failure, Day and Daniel, 1985, predict that the effects of desiccation and cracking may increase the hydraulic conductivity by as much as 1,000 times the value measured in the laboratory.

Since the effects of desiccation can render a liner useless, it is necessary to take precautions against this problem. The most effective way to guard against desiccation is to keep the surface of the compacted clay liner from being in direct communication with the atmosphere. By limiting the exposure to the surface air, moisture losses due to evaporation may be greatly reduced.

Methods used to protect compacted soil liners from desiccation commonly include the use of geomembrane covers, the spraying the liner with bituminous sealers, or the covering the completed liner with another layer of soil. If the liner can not be covered, its surface should be periodically sprayed with water to limit moisture loss from within the soil fabric. It should be noted, however, that if water is added to the liner surface, care should be taken to avoid excessive wetting. Excessive moisture can result in instability and can lead to the failure of the clay liner.

WDNR, for example, requires that a soil liner with a thickness of at least 0.3 m be placed directly above the compacted soil liner. This additional soil layer serves two distinct purposes. First, this layer protects the underlying compacted soil liner from desiccation. Second, constructed of coarse sand or gravel, this layer will serve as a drainage blanket and as a leachate removal system (Gordon et. al., 1990).

Leachate Removal

Even the most perfectly constructed compacted soil liners will provide poor protection against the transport of landfill leachates, if leachate materials are allowed to accumulate and stand on the liner. The volume of leachate passing through the liner is directly related to the depth of the leachate standing on the liner surface. While it is beyond the scope of this paper to discuss leachate removal systems, removal systems are integral to the effective performance of compacted soil liner systems.

Sloping of the clay liner surface (the EPA requires a minimum surface gradient of 2%), in conjunction with granular soil drainage blankets, geonets and perforated pipe collection systems can be used to limit the height of leachate standing on the surface of the liner. The more efficient the collection system, the less leachate will be available for transport through the liner.

Monitoring

Quality assurance is a major concern associated with the construction of compacted soil liners. It has been found that the ideal hydraulic conductivity values defined in the lab are rarely duplicated in the field. Discrepancies can result from a variety of sources. These sources can range from the non-homogeneous nature inherent to all soils, to defects caused during construction. For this reason, it is important to continuously test and monitor the liner. Testing should begin with conception and continuing through service.

During the design process, great care should be taken to avoid over estimating the ability of a given soil to restrict flow. Permeability tests, performed in the lab, use very small samples (25 mm – 100 mm). While these tests will yield a good results as to how a fluid might flow through the soil under ideal conditions, it fails to model the non-homogeneity present in most soils. Small samples are also poor models for predicting the flows resulting from liner defects. Daniel, 1984, examined several existing earthen liners for which leakage rates could be quantified. Field hydraulic conductivity values were back calculated from these observed leakage rates and were found to be 5 to 100,000 times greater than those determined by the laboratory (Trautwein et. al., 1990). Daniel’s study is proof that testing beyond the lab must be performed if the effectiveness of a compacted soil liner is to be assured.

Monitoring Methods

Test pads have become a popular technique for the acquisition of accurate, large-scale design information for compacted soil liner projects. Test pads, as illustrated in the example pertaining to clod defects, are used to identify potential problems in the design or construction process. By using a test pad, larger areas can be tested under field conditions with minimal sample disturbance. Figure 7 shows the typical layout of a liner test pad.

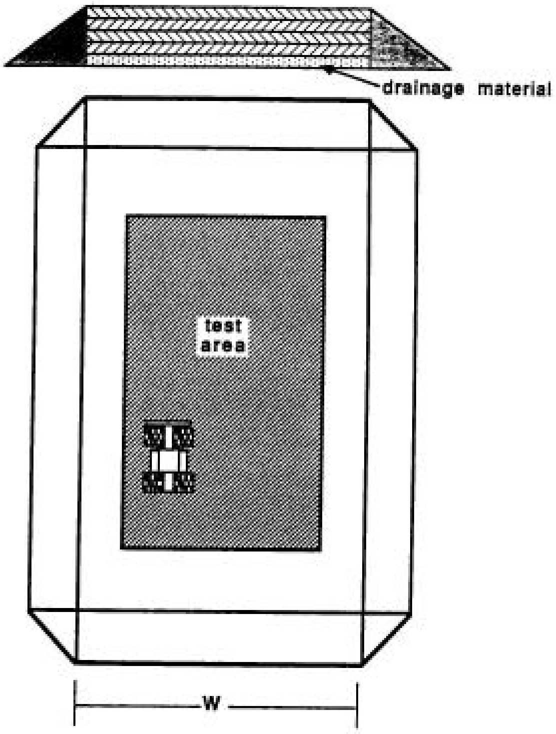

Figure 7: Typical Layout of a Compacted Soil Liner Test Pad.

Another method for acquiring representative hydraulic conductivity data is to perform field test investigations. As with test pads, field tests allow for the testing of larger volumes of soil with minimal soil disturbance. The most common forms of field tests include porous probes, boreholes, infiltrometers and underdrains. Figure 8 displays the basic construction of each of these field-tests.

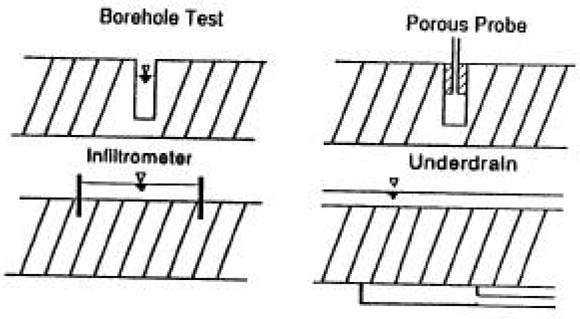

Figure 8: Hydraulic Conductivity Field-Tests.

Porous probes are moderately priced, convenient and offer quick testing. Porous probes do however, suffer from a fairly small area of influence. The volume of permeated soil is typically smaller than that tested in the lab. Figure 9 demonstrates how a typical porous prove test is performed.

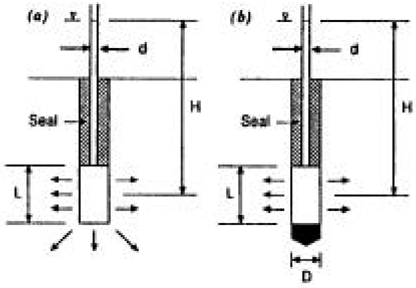

Figure 9: Porous Probe Field-Test.

Borehole tests require more time than the porous probe but are able to permeate an area roughly 30 times the size of the typical laboratory test. Borehole tests generally require several days to weeks to perform. Borehole tests are commonly performed with either a Boutwell permeameter or a Guelph permeameter. Figure 10 is a diagram of the standard Boutwell permeameter test.

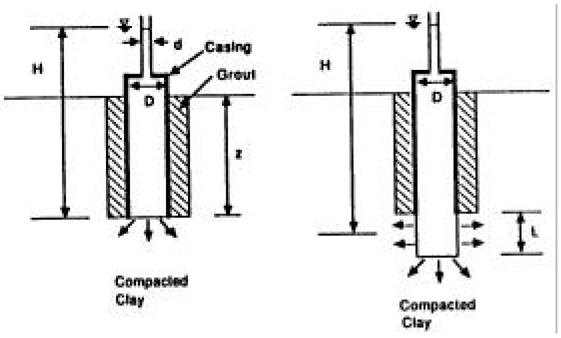

Figure 10: Standard Boutwell Permeameter Test

Infiltration tests are expensive to run and require several weeks to months to perform. The benefit associated with infiltration testing is that a large volume of soil can be permeated (a significantly larger area than any of the previously discussed field-test methods). There are several types of infiltration testing devices. These devices range from simple to complex. While some infiltrometers simply monitor the rate of infiltration, others can counteract testing errors such as pressure, suction and lateral flow. An example of a Sealed Double-Ring Infiltrometer is shown below.

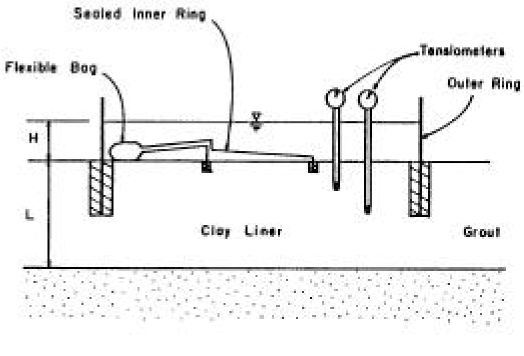

Figure 11: Sealed Double Ring Infiltrometer (SDRI) Field-Test.

Underdrains are moderate in cost, have testing times in the range of several months to a year, and can test very large volumes of soil. Underdrains or lysimeter pans are generally constructed in the field, and vary in size and shape (Trautwein). A typical underdrain system is shown below (Figure 12).

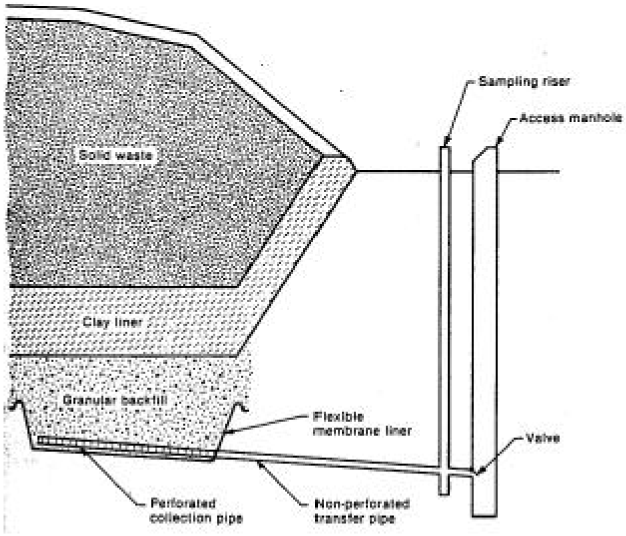

Figure 12: Underdrain Field-Test.

Phase Specific Monitoring

There are three general phases related to compacted soil liner systems: Pre-construction, Construction and Service. Monitoring during the Pre-construction Phase consists of laboratory tests, test pad studies and field-tests. The primary purpose of monitoring during the Pre-construction Phase is to gather information, which could lead, to the improvement and optimization of the design specifications and construction process.

Monitoring during the Construction Phase is extremely important as it is used to assure that standards of construction are being met. This phase however, is also the most difficult phase to monitor. Tests at this phase are mostly limited to laboratory tests that may not give representative results of the true field conditions. Significant improvement of testing techniques can be made for this phase can be made.

Service Phase monitoring is performed with underdrains or lysimeters, which have been installed, during construction, under the completed clay liner. The purpose of Service Phase monitoring is to insure that the liner is functioning as designed. If contaminates are being transported through the liner, samples captured by the underdrain will reveal these contaminates and will serve as an indicator of the problem. Observation wells, used in conjunction with underdrains, serve as a secondary monitoring device to assure that contaminates are not being disseminated through the ground water.

Conclusions

Compacted clay liner systems are capable of achieving hydraulic conductivity values much lower than the EPA's minimum value of 1×10^{-7} cm/s. Values in the range of 10^{-8} and even 10^{-9} can be achieved with careful construction and quality assurance. With such low levels of hydraulic conductivity, the compacted clay liner is a viable choice as a municipal landfill liner system.

To achieve hydraulic conductivity values in this range, several aspects of the clay liner must be considered.

- The EPA requires a minimum liner thickness of 0.9 m, a minimum thickness or 1.2 m to 1.8 m might be more appropriate given WDNR's record of performance over the past 20 to 30 years.
- The ideal placement conditions for the compacted clay is achieved with a high Dry Density and a Moisture Content wet of the Line of Optimums.
- Compaction should be performed with a heavy Sheep's Foot Roller as the kneading action will lead to a dispersed clay structure.
- When placing lifts, the depth of each lift must not be greater than the depth of penetration for the Sheep's Foot Roller.
- A minimum of 5 passes by the Sheep's Foot Roller is generally required to achieve compaction.
- Exposed Lift surfaces must be scarified to a minimum depth of 25 mm before the placement of the next lift to ensure adequate lift integration.
- Clods and non-homogeneous materials must be reduced and eliminated to achieve low values of hydraulic conductivity. The EPA requires that all clods larger than 25 mm must be mechanically broken down.
- As a liner is constructed it must be protected from desiccation.
- Leachate must be removed from the surface of the liner, as the quantity of leachate passing through the liner is directly related to the amount of leachate left standing on the liner.
- Proper monitoring throughout all phases of the liner's life will assure that the liner is and does perform as designed.

By giving consideration to design, construction and life long monitoring techniques, a compacted clay liner will become an effective barrier against leachate leakage and transport. With proper care, a compacted clay liner system is a viable solution for landfill containment.

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