651.1080 Appendix 10D—Geotechnical, Design, and Construction Guidelines

Appendix 10D Geotechnical, Design, and Construction Guidelines

Introduction

The protection of surface and ground water and the proper utilization of wastes are the primary goals of waste storage ponds and treatment lagoons. Seepage from these structures creates potential risks of pollution of surface water and underground aquifers. The permeability of the soil in the boundaries of a constructed waste treatment lagoon or waste storage pond directly influences the potential for downward or lateral seepage of the stored wastes.

Many natural soils on the boundaries of waste treatment lagoons and waste storage ponds at least partly seal as a result of introduction of manure solids into the reservoir. Physical, chemical, and biological processes occur that reduce the permeability of the soil-liquid interface. Suspended solids settle out and physically clog the pores of the soil mass. Anaerobic bacteria produce by-products that accumulate at the soil-liquid interface and reinforce the seal. The soil structure can also be altered in the process of metabolizing organic material. Chemicals in waste, such as salts, can disperse soil, which may be beneficial in reducing seepage. Researchers have reported that, under the right conditions, the permeability of the soil can be decreased by up to several orders of magnitude in a few weeks following contact with waste in a waste storage pond or treatment lagoon. These guidelines have been developed under the premise that the permeability decrease induced by the manure should not be counted on as the sole means of ground water protection. However, the guidelines do propose recognition of sealing to the extent of one order of magnitude for soils with a clay content exceeding 5 percent for ruminant manures and 15 percent for monogastric animal manures.

General design considerations

The following guidelines[1] address the design and construction techniques needed to overcome certain soil limitations. These guidelines should be considered in the planning, design, construction, and operation of agricultural waste management components including waste treatment lagoons and waste storage ponds.

Soil and foundation characteristics are critical to design, installation, and safe operation of successful waste treatment lagoons or waste storage ponds. Waste impoundments must be located in soils with acceptable permeabilities or be lined.

[1] These guidelines are an update and augmentation of material previously published in SNTC Technical Note 716, "Design and Construction Guidelines for Considering Seepage from Agricultural Waste Storage Ponds and Treatment Lagoons." SNTC Technical Note 716 has been canceled.

Soil properties

NRCS soil mechanics laboratories have a data base of permeability tests performed on over 1,100 compacted soil samples. Experienced NRCS engineers have analyzed these data and correlated permeability rates with soil index properties and degree of compaction of the samples. Tables 10D–1 to 10D–3 are based on this analysis and provide general guidance on the probable permeability of the described soil groups. The grouping of soils in table 10D–1 is based on the percent fines and Atterberg limits of the soils. Fines are those particles finer than the No. 200 sieve. Table 10D–2 provides assistance in converting from the Unified Soil Classification to one of the four permeability groups.

Table 10D–1 Grouping of soils according to their estimated permeability

Group	Description
I	Soils that have less than 20% passing a No. 200 sieve and have a Plasticity Index (PI) less than 5.
II	Soils that have 20% or more passing a No. 200 sieve and have PI less than or equal to 15. Also included in this group are soils with less than 20 percent passing the No. 200 sieve with fines having a PI of 5 or greater.
III	Soils that have 20% or more passing a No. 200 sieve and have a PI of 16 to 30.
IV	Soils that have 20% or more passing a No. 200 sieve and have a PI of more than 30.

Table 10D–2 Unified classification versus soil permeability groups 1/

Unified classification	Permeability group 2/ I	II	III	IV
CH	N	N	S	U
MH	N	S	U	S
CL	N	S	U	S
ML	N	U	S	N
CL-ML	N	A	N	N
GC	N	S	U	S
GM	S	U	S	S
GW	A	N	N	N
SM	S	U	S	S
SC	N	S	U	S
SW	A	N	N	N
SP	A	N	N	N
GP	A	N	N	N

1/ ASTM Method D-2488 has criteria for use of index test data to classify soils by the Unified Soil Classification System.

2/ A = Always in this permeability group.
N = Never in this permeability group.
S = Sometimes in this permeability group (less than 10 percent of samples fall in this group).
U = Usually in this permeability group (more than 90 percent of samples fall in this group).

Permeability of soils

Table 10D–3 shows the percentage of each group for which a permeability test measured a k value of 0.0028 feet per day (1×10^{-6} cm/s) or less. The table also shows the median k value for the group in feet per day. A value of the coefficient of permeability of 0.0028 feet per day (1×10^{-6} cm/s) was selected for the median value studied. For typical NRCS designed structures, this value results in an acceptable seepage loss. As discussed later in this section, sealing by manure solids and biological action will most likely produce an additional order of magnitude reduction in permeability in the soils at grade.

Table 10D–3 summarizes a total of 1,161 tests. Where tests are shown at 85 to 90 percent of maximum density, over 75 percent of the tests were at 90 percent of maximum dry density. Where 95 percent degree of compaction is shown, data include both 95 and 100 percent degree of compaction tests. Over 80 percent of this group of tests was performed at 95 percent of maximum density. Based on these data, the following general statements can be made for the four soil groups:

Group I—These soils have the highest permeability and could allow unacceptably high seepage losses. Because the soils have a low clay content, permeability values may not be substantially reduced by manure sealing, and will probably exceed 10^{-6} centimeters per second.

Group II—These soils generally are less permeable than the Group I soils, but lack sufficient clay to be included in Group III.

Group III—These soils generally have a very low permeability, good structural features, and only low to moderate shrink-swell behavior.

Caution: Some soil in Group III is more permeable than indicated by the percent fines and PI value because they contain a high amount of calcium. The presence of a high amount of calcium results in a flocculated or aggregated structure in the soils. These soils often result from the weathering of high calcium parent rock, such as limestone. Soil scientists and published soil surveys are helpful in identifying these soil types. Dispersants, such as tetrasodium polyphosphate, can alter the flocculated structure of these soils by replacement of the calcium with sodium on the clay particles (See the section, *Design and construction of clay lines treated with soil dispersants*). Because manure contains salts, it can be helpful in dispersing the structure of these soils, but design should probably not rely solely on manure as the additive for these soil types.

Group IV—Normally, these soils have a very low permeability. However, because of their sometimes blocky structure, they can experience high seepage losses through cracks that can develop when the soil is allowed to dry. They possess good attenuation properties if the seepage does not move through cracks in the soil mass.

Table 10D–3 Summary of soil mechanics laboratories permeability test data

Soil group	Percent of ASTM D698 dry density	Number of observations	Median K (cm/s)	Median K (ft/d)	Percent of tests where k < 0.0028 (ft/d)
I	85-90	27	7.2×10^{-4}	2.0	0
I	95	16	3.5×10^{-4}	1.0	0
II	85-90	376	4.8×10^{-6}	0.014	30
II	95	244	1.5×10^{-6}	0.004	45
III	85-90	226	8.8×10^{-7}	0.0025	59
III	95	177	2.1×10^{-7}	0.0006	75
IV	85-90	41	4.9×10^{-7}	0.0014	72
IV	95	54	3.5×10^{-8}	0.0001	69

In situ soils with acceptable permeability

Natural soils that are classified in permeability Groups III or IV generally have permeability characteristics that result in acceptable seepage losses. NRCS permeability data bases show these soils usually have coefficients of permeability of 1 x 10^{-6} centimeters per second (0.0028 ft/d) or less if the soils are at dry densities equivalent to at least 90 percent of their Standard Proctor (ASTM D698) maximum dry densities. Based on the literature reviewed, introduction of manure provides a further decrease in the permeability rate of at least 1 order of magnitude. Such sealing is thought to be a result of physical, chemical, and biological processes. Suspended solids settle or filter out of solution and physically clog the pores of the soil mass. Anaerobic bacteria produce by-products that accumulate at the soil-water interface and reinforce the seal, and in the process of metabolizing organic material can alter the soil structure. Chemicals in animal waste, such as salts, can disperse soil, which may be beneficial in reducing seepage. Special design measures generally are not necessary where agricultural waste storage ponds or treatment lagoons are constructed in these soils, provided that the satisfactory soil type is at least 2 feet thick below the deepest excavation limits and sound construction procedures are used. This also assumes that no highly unfavorable geologic conditions, such as limestone formations with extensive caves or solution channels, occur at the site.

Soils in Groups III and IV that have a blocky structure or desiccation cracks should be disked, watered, and recompacted to destroy the structure in the soils and provide an acceptable permeability. The depth of the treatment required should be based on design guidance given in the section, *Construction considerations for compacted clay liners.* High calcium clays should be modified with soil dispersants to achieve the target permeability goals based on the guidance given in the section, *Design and construction of clay liners treated with soil dispersants.*

Definition of pond liner

Liners are relatively impervious barriers used to reduce seepage losses to an acceptable level. A liner for a waste impoundment can be constructed in several ways. When soil is used as a liner, it is often called a clay blanket or impervious blanket. A simple method of providing a liner for a waste storage structure is to improve the soils at the excavated grade by disking, watering, and compacting them to a thickness indicated by guidelines in following sections. Soils with suitable properties can make excellent liners, but the liners must be designed and installed correctly. Soil has an added benefit in that it provides an attenuation medium for many types of pollutants.

The three options when the soil at the excavated grade is unsuitable to serve as a liner for a waste impoundment are:

- Treat the soil at grade with bentonite or a soil dispersant.
- Construct the soil liner by compacting imported clay from a nearby borrow source onto the bottom and sides of the waste impoundment.
- Use concrete or synthetic materials, such as geosynthetic clay liners (GCL's) and geomembranes.

Treat the soil at grade with bentonite or a soil dispersant. Problem soils in Group III may be treated with dispersants to attain a satisfactory soil liner. (See the section, *Design and construction of clay liners treated with soil dispersants.*) Soils in Groups I and II that are unsuitable in their natural state for use as liners can often be treated with bentonite to produce a satisfactory soil liner. Bentonite or soil dispersants should be added and mixed well into a soil prior to compaction. Brown (1991) describes techniques for constructing bentonite treated liners.

High quality sodium bentonite with good swell properties should be used for construction of clay liners using Group I and II soils. The highest quality bentonite is mined in Wyoming and Montana. NRCS soil mechanics laboratories have found it important to use the same type and quality of bentonite that will be used for construction in the laboratory permeability tests used to design the soil-bentonite mixture. Both the quality of the bentonite and how finely ground the product is before mixing with the soil affect the final permeability rate of the mixture. It is important to work closely with both the bentonite supplier and the soil testing facility when designing treated soil liners.

Construct the soil liner by compacting imported clay from a nearby borrow source onto the bottom and sides of the waste impoundment—Compaction is often the most economical method for constructing liners if suitable soils are available nearby.

Use concrete or synthetic materials, such as geosynthetic clay liners (GCL's) and geomembranes—Concrete has advantages and disadvantages for use as a liner. It will not flex to conform to settlement or shifting of the earth. In addition, some concrete aggregates may be susceptible to attack by continued exposure to chemicals contained in or generated by the waste. Concrete serves as an excellent floor from which to scrape solids. It also provides a solid support for equipment, such as tractors or loaders. Some bedrock may contain large openings caused by solutioning and dissolving of the bedrock by ground water. Common types of solutionized bedrock are limestone and gypsum. When existence of sinks or openings is known or identified during the site investigation, these areas should be avoided and proposed facility located elsewhere. However, when these conditions are discovered during construction or alternate sites are not available, concrete liners may be required to bridge the openings, but only after the openings have been properly treated and backfilled.

Geomembranes and GCL's are the most impervious types of liners if designed and installed correctly. Care must be exercised both during construction and operation of the waste impoundment to prevent punctures and tears. Forming seams in the field for geomembranes can require special expertise. GCL's have the advantage of not requiring field seaming, but the overlap required to provide a seal at seams is an extra expense. Geomembranes and GCL's must contain ultraviolet inhibitors if they will be exposed. Designs should include provision for their protection from damage during cleaning operations.

Four conditions where a liner should be considered

Four conditions for which a designer should consider seepage reduction beyond that provided by the natural soil at the excavation boundary are listed below.

Proposed site is located where any underlying aquifer is at a shallow depth and not confined and/or the underlying aquifer is a domestic or ecologically vital water supply. State or local regulations may prevent locating a waste storage structure within a given distance from such features.

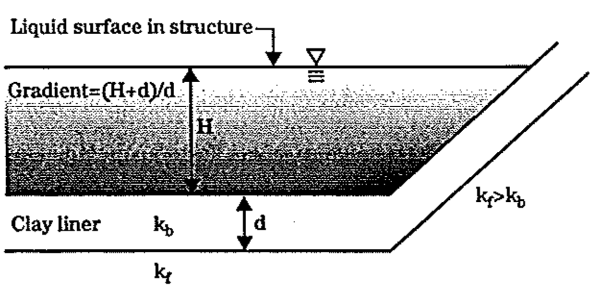
Excavation boundary of a site is underlain by less than 2 feet of soil over bedrock. Bedrock that is near the soil surface is often fractured or jointed because of weathering and stress relief. Many rural domestic and stock water wells are developed in fractured rock at a depth of less than 300 feet. Some rock types, such as limestone and gypsum, may have wide, open solution channels caused by chemical action of the ground water. Soil liners may not be adequate to protect against excessive leakage in these bedrock types. Concrete or geomembrane liners may be appropriate for these sites. However, even hairline openings in rock can provide avenues for seepage to move downward and contaminate subsurface water supplies. Thus, a site that is shallow to bedrock can pose a potential problem and merits the consideration of a liner. Bedrock at a shallow depth may not pose a hazard if it has a very low permeability and has no unfavorable structural features. An example is massive siltstone.

Excavation boundary of a site is underlain by soils in Group I—Coarse grained soils with less than 20 percent low plasticity fines generally have higher permeability and have the potential to allow rapid movement of polluted water. The soils are also deficient in adsorptive properties because of their lack of clay. Relying solely on the sealing resulting from manure solids when Group I soils are encountered is not advisable. While the reduction in permeability from manure sealing may be 1 to 3 orders of magnitude, the final resultant seepage losses are still likely to be excessive, and a liner should be used.

Excavation boundary of a site is underlain by some soils in Group II or problem soils in Group III (flocculated clays) and Group IV (highly plastic clays that have a blocky structure)—Soils in Group II may or may not require a liner. Documentation through laboratory or field permeability testing or by other acceptable alternatives is advised. An acceptable alternative would be correlation to similar soils in the same geologic or physiographic areas for which test data are available. Higher than normal permeability for flocculated clays and clays that have a blocky structure has been discussed. These are special cases, and most soils in Groups III and IV will not need a liner. Note that a liner may be constructed by treating a determined required thickness of unfavorable soils occurring at grade.

The above conditions do not always dictate a need for a liner. Specific site conditions can reduce the potential risks otherwise indicated by the presence of one of these conditions. For example, a thin layer of soil over high quality rock, such as an intact shale, is less risky than if the thin layer is over fractured or fissured rock.

Figure 10D–1 Definition of terms for clay liner and seepage calculations



where:
- H = Head of waste liquid in waste impoundment
- k_f = Permeability of foundation
- d = Thickness of liner
- k_b = Permeability of liner

Specific discharge

(a) Introduction

No soil or artificial liner, even concrete or a geomembrane liner, can be considered impermeable. To limit seepage to an acceptable level, regulatory agencies may specify a maximum allowable permeability value in liners. A criterion often used for clay liners is that the soils at grade in the structure, or the clay liner if one is used, must have a permeability of 1×10^{-7} centimeters per second or less. However, using only permeability as a criterion ignores other factors defining the seepage from an impoundment. Seepage is calculated from Darcy's Law (covered in the following section), and seepage calculations consider the permeability of the soil and the hydraulic gradient for a liner at a site.

(b) Definition of specific discharge

The term *specific discharge*, or unit seepage, is the seepage rate for a unit cross-sectional area of a pond. It is defined as follows from Darcy's Law. The hydraulic gradient for a clay liner is defined in figure 10D–1.

Given:

$$Q = k\left(\frac{(H+d)}{d}\right)A \quad \text{(Darcy's Law)}$$

Where:
- Q = Total seepage through area A (L^3/T)
- k = Coefficient of permeability (hydraulic conductivity) ($L^3/L^2/T$)
- $\frac{(H+d)}{d}$ = Hydraulic gradient (L/L)
- H = Vertical distance measured between the top of the liner and required volume of the waste impoundment (figs. 10D–1, 10D–14, 10D–15, and 10D–21) (L)
- d = Thickness of the soil liner (fig. 10D–1) (L)
- A = Cross-sectional area of flow (L^2)
- L = Length
- T = Time

Rearrange terms:

$$\frac{Q}{A} = \frac{k(H+d)}{d} \qquad (L/T)$$

By definition, unit seepage or specific discharge, ν, is Q/A:

$$\nu = \frac{k(H+d)}{d} \qquad (L^3/L^2/T)$$

The units for specific discharge are $L^3/L^2/T$. However, these units are commonly reduced to L/T.

If a coefficient of permeability of 1 x 10^{-7} centimeters per second is regarded as acceptable, then an allowable specific discharge value can be calculated. Typical NRCS waste impoundments have a depth of waste liquid of about 9 feet and a liner thickness of 1 foot. Then, a typical hydraulic gradient of (9+1)/1 = 10 is a reasonable assumption. To solve for an allowable specific discharge, using previous assumptions that an acceptable permeability value is 1 x 10^{-7} centimeters per second, and a hydraulic gradient of 10, substituting in the equation for ν:

$$\begin{aligned} \nu_{\text{allowable}} &= k\frac{(H+d)}{d} \\ &= 1\times10^{-7}\ \text{cm/s}\times10 \\ &= 1\times10^{-6}\ \text{cm/s} \\ &= 0.0028\ \text{ft/d} \end{aligned}$$

However, if one assumes at least one order of magnitude of reduction in permeability will occur, the initial permeability can be 10 times greater (1 x 10^{-6} centimeters per second) and the final value for permeability will approach 1 x 10^{-7} centimeters per second after sealing. Then, an allowable initial specific discharge of will be:

$$\begin{aligned} \nu_{\text{initial allowable}} &= k\frac{(H+d)}{d} \\ &= 1\times10^{-6}\ \text{cm/s}\times10 \\ &= 1\times10^{-5}\ \text{cm/s} \\ &= 0.028\ \text{ft/d} \end{aligned}$$

As noted previously, allowable specific discharge actually has units of cubic feet per square foot per day, but for convenience the units are often stated as foot per day. Note that some State or local regulations may not permit taking credit for an order of magnitude reduction in permeability resulting from manure sealing. The State or local regulations should be used in design for a specific site.

Specific discharge or unit seepage is the quantity of water that flows through a unit cross-sectional area composed of pores and solids per unit of time. It has units of $L^3/L^2/T$ and is often simplified to L/T. Because specific discharge expressed as L/T has the same units as velocity, specific discharge is often misunderstood as representing the average rate or velocity of water moving through a soil body rather than a quantity rate flowing through the soil. Because the water flows only through the soil pores, the cross sectional area of flow is computed by multiplying the soil cross section (A) by the porosity (n). The seepage velocity is then equal to the unit seepage or specific discharge, v, divided by the porosity of the soil, n. Seepage velocity = (v / n). In compacted liners, the porosity usually ranges from 0.3 to 0.5. The result is that the average linear velocity of the seepage flow is two to three times the specific discharge value. The units of seepage velocity are L/T.

(c) Design of compacted clay liners

To determine the required thickness of clay liner, rearrange the above equation for specific discharge using test values for permeability and the depth of waste liquid in the waste impoundment. Alternatively, a given value for the thickness of liner to be constructed may be assumed, and the minimum permeability required to meet a target specific discharge for the depth of waste liquid in the facility can be determined. Detailed design examples and equation derivations are shown later in this section.

Detailed design steps for clay liners

The suggested steps for design of a compacted soil liner are:

Step 1—Size the structure to achieve the desired storage requirements within the available construction limits and determine this depth or the height, H, of storage needed.

Step 2—Either estimate the permeability from the previous information showing estimated permeability values for Groups III and IV, or use the value attained in laboratory permeability tests. Field tests on compacted liners could also supply permeability design information. Use a value for allowable discharge of $v = 1 \times 10^{-5}$ centimeters per second (0.028 ft/d) if manure sealing can be credited, or 1×10^{-6} centimeters per second (0.0028 ft/d) if it is not credited. Calculate a preliminary liner thickness (d) to meet the allowable specific discharge criterion using the following equation. Derivation of the equation is shown later in this section. Terms are defined in figure 10D–1.

$$d = \frac{k \times H}{v - k}$$

Step 3—If the k value used for the liner is equal to or greater than the assumed allowable specific discharge, meaningless results are attained for d, the calculated thickness of the liner in the equation above. The allowable specific discharge goal cannot be met if the liner soils have k values equal to or larger than the assumed allowable specific discharge.

Step 4—The calculated thickness of liner required is very sensitive to the value of permeability used and the assumed allowable specific discharge value. Often, the required liner thickness can be reduced most economically by decreasing the soil permeability. Small changes in the soil liner specifications, including degree of compaction, rate of bentonite addition, and water content at compaction, can drastically affect the permeability of the clay liner soil.

Step 5—An alternative design approach is to use a predetermined desirable thickness for the liner; for example, 1 foot, and then calculate what permeability is required to meet the specific discharge target. The equation used is derived later in this section, and is as follows:

$$k = \frac{v \times d}{H + d}$$

This design approach requires that measures, such as special compaction or addition of bentonite or other soil additives, be then taken to ensure the calculated allowable permeability or a lesser value is attained.

Step 6—Cautions

The liner soil must be filter-compatible with the natural foundation upon which it is compacted. Filter compatibility is determined by criteria in NEH Part 633 (chapter 26). As long as the liner soil will not pipe into the foundation, no limit need be placed on the hydraulic gradient across the liner. Filter compatibility is most likely to be a significant problem when very coarse soil, such as poorly graded gravels and sands, occurs at a site and a liner is being placed directly on this soil.

The minimum recommended thickness of a compacted natural clay liner is 1 foot. Clay liners constructed by mixing soil dispersants or bentonite with the natural soils at a site are recommended to have a minimum thickness of 6 inches. These minimum thicknesses are based on construction considerations rather than calculated values for liner thickness requirement from the specific discharge equations. In other words, if the specific discharge equations indicate only a 7-inch thickness of compacted natural clay is needed to meet suggested seepage criteria, a 1-foot-thick blanket would still be recommended because constructing a 7-inch natural clay blanket with integrity would be difficult.

Natural and constructed liners must be protected. Natural and constructed liners must be protected against damage by mechanical agitators or other equipment used for cleaning accumulated solids from the bottoms of the structures. Liners should also be protected from the erosive forces of waste liquid flowing from pipes during filling operations.

Soil liners may not provide adequate confidence against ground water contamination if foundation bedrock relatively near the pond waste impoundment bottom contains large, connected openings, where collapse of overlying soils into the openings could occur. These bedrock conditions were discussed in detail previously. Structural liners of reinforced concrete or geomembranes should be considered because the potential hazard of direct contamination of ground water is significant.

Liners should be protected against puncture from animal traffic and roots from trees and large shrubs. The subgrade must be cleared of stumps and large angular rocks before construction of the liner.

If a clay liner is allowed to dry, it may develop drying cracks or a blocky structure and will then have a much higher permeability. Desiccation can occur during the initial filling of the waste impoundment and later when the impoundment is emptied for cleaning or routine pumping. Disking, adding water, and compaction are required to destroy this structure. A protective insulating blanket of less plastic soil may be effective in protecting underlying more plastic soil from desiccation during these exposure periods.

State and Federal regulations may be more stringent than the design guidelines given, and they must be considered in the design. Examples later in this section address consideration of alternative guidelines.

Construction considerations for compacted clay liners

(a) Thickness of loose lifts

The permissible loose lift thickness of clay liners depends on the type of compaction roller used. If a tamping or sheepsfoot roller is used, the roller teeth should fully penetrate through the lift being compacted into the previously compacted lift to achieve bonding of the lifts. A loose lift thickness of 9 inches is commonly used by NRCS specifications. If the feet on rollers cannot penetrate the entire lift during compaction, longer feet or a thinner lift should be specified. A loose layer thickness of 6 inches may be needed for some tamping rollers that have larger pad type feet that do not penetrate as well. Thinner lifts could significantly affect construction costs.

(b) Method of construction

(1) Bathtub

This method of construction consists of a continuous thickness of soil compacted up and down or across the slopes (fig. 10D–2). This construction is clearly preferable to the stair step method because inter-lift seepage flow through the sides of the excavation is less. This method also lends itself well to the thinner lifts used by NRCS. Side slopes should be 3H:1V or flatter to use this method. Shearing of the soil by the equipment on steeper slopes is a problem. To prevent shearing of the compacted soil, the slope used must be 3H:1V or flatter so that equipment will exert more normal pressure on the slope than downslope pressure.

(2) Stair step

This method of construction is illustrated in figure 10D–2. It would probably be needed for side slopes steeper than about 3H:1V. A much thicker blanket, measured normal to the slope, will result compared to the bathtub method of construction. This is a positive factor in seepage reduction, but it will probably be more expensive because of the larger volume of soil required. Another advantage of this method is that the thicker blanket reduces the impact of shrinkage cracks, erosive forces, and potential mechanical damage to the liner. If the main concern is leakage through the bottom of the lagoon rather than the sides, the method has fewer advantages over the bathtub method. Another disadvantage of this method is that a larger volume of excavation is required to accommodate the thicker blanket.

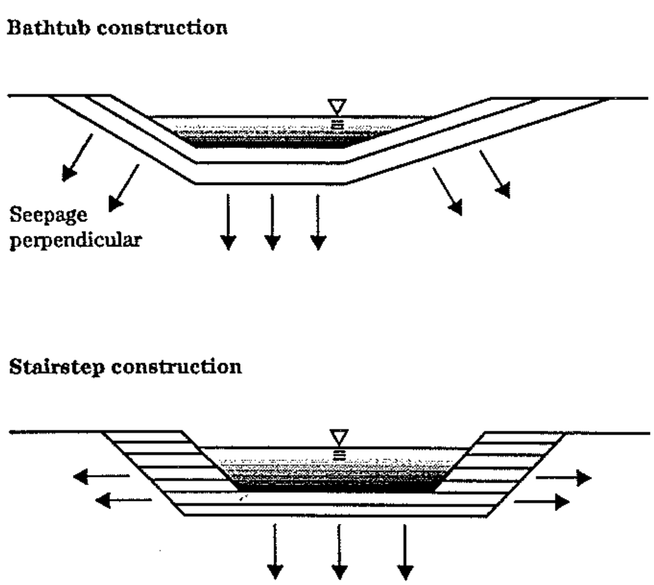
(c) Soil type

(1) Classification

Group IV soil has a plasticity index (PI) greater than 30 and is usually considered desirable. However, soil that has a PI value greater than 40 is not desirable for several reasons. Although more highly plastic clays may have very low laboratory test permeability values, these clays can develop severe shrinkage cracks. Preferential flow through the desiccated soil often results in a higher than expected permeability. Figure 10D–3 illustrates the structure that can occur with plastic clays where clods are present.

Highly plastic clays are also difficult to compact properly. Special effort should be directed to processing the fill and degrading any clods in high plasticity clays to prevent the problems illustrated with figure 10D-3.

Figure 10D–2 Methods of liner construction (After Boutwell, 1990)

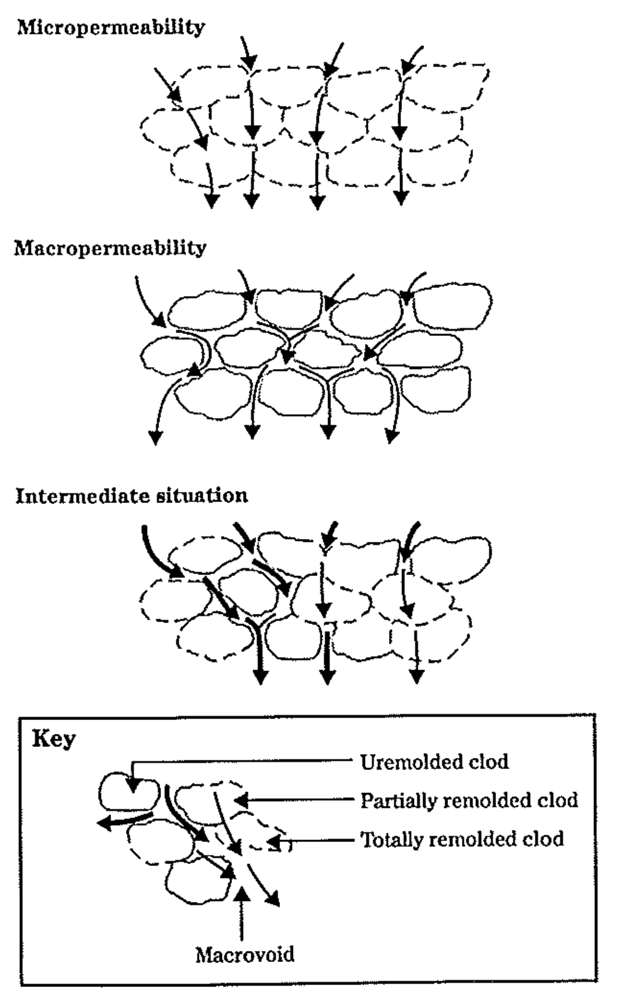


High plasticity clays may be covered with a blanket of insulating soil, such as an SM soil, to protect the liner from desiccation while the waste impoundment is being filled, particularly if filling will occur during hot, dry months.

(2) Size of clods

The size and dry strength of clay clods in soil prior to compaction have a significant effect on the final quality of a clay liner. Large, dry clods of plastic clays are extremely difficult to degrade and moisten thoroughly. High speed rotary pulverizers are sometimes needed if conditions are especially unfavorable. Adding water to the soil is difficult because water penetrates the clods slowly.

Figure 10D–3 Macrostructure in highly plastic clays with poor construction techniques (from Hermann 1987)



(d) Natural water content of borrow

(1) Dry conditions in the borrow

Dry, highly plastic clays are most likely extremely cloddy. Time must be allowed for added water to penetrate larger clods before processing. Prewetting the borrow area may reduce the severity of this problem. Because water slowly penetrates any clods, adding significant amounts of water to a plastic clay is difficult if this addition is delayed until processing on the compacted fill.

(2) Wet conditions in the borrow

If the natural water content of the borrow soil is significantly higher than optimum water content, achieving the required degree of compaction may be difficult. A good rule-of-thumb is that a soil will be difficult to compact if its natural water content exceeds about 90 percent of the theoretical saturated water content at the dry density to be attained. The following procedure can help to determine if a wet condition may be present.

Step 1—Measure the natural water content of the soil to be used as a borrow source for the clay liner being compacted.

Step 2—Measure the maximum dry density and optimum water content of the soil by the appropriate Proctor test (generally ASTM D 698, method A).

Step 3—Determine from suggestions in this guidance document, or from laboratory permeability tests, to what degree of compaction are the clay soils to be compacted (generally 90, 95, or 100 percent of maximum dry density).

Step 4—Calculate the theoretical saturated water content at the design dry density of the liner:

$$w_{sat}(\%) = \left(\frac{\gamma_{water}}{\gamma_d} - \frac{1}{G_s}\right) \times 100$$

Step 5—Calculate 90 percent of the theoretical saturated water content.

Step 6—If the natural water content of the soil is more than 1 or 2 percent wet of this calculated upper feasible water content, the clays will be difficult to compact to the design density without drying. In most cases drying clay soils simply by disking is somewhat ineffective. It would be more practical to delay construction to a drier part of the year when the borrow source is at a lower water content. In some cases the borrow area can be drained several months before construction. This would allow gravity drainage to decrease the water content to an acceptable level.

(e) Method of excavation and methods of processing

(1) Clods in borrow soil

If borrow soil is plastic clays at a low water content, it will probably have large, durable clods. Disking may be effective for some soils at the proper water content, but pulverizer machines may be required. To attain the highest quality liner, the transported fill should be processed with either a disk or a pulverizer before using a tamping roller. Equipment requirements depend on the severity of the clodiness and the water content of the soil.

(2) Placement of lifts

Preferential flow paths can be created if lifts of the clay liner are not staggered or placed in alternating directions. Continuous processing in one direction without adequate disking and bonding can also result in flow paths between lifts. Careful planning of the liner construction will avoid these problems.

(f) Macro-structure in plastic clay soils

Clods can create a macro-structure in a soil that results in higher than expected permeability because of preferential flow along the interfaces between clods. Figure 10D–3 illustrates a structure that can result from inadequate wetting and processing of plastic clay. The permeability of intact clay particles may be quite low, but the overall permeability of the mass is high because of flow between the intact particles.

(g) Dry density and optimum water content

(1) Introduction

Compaction specifications normally require a minimum dry density (usually referenced to a specified compaction test procedure) and an accompanying range of acceptable water contents (referenced to the same compaction test procedure). This method of fill specification may not be as applicable to design of clay liners. A given permeability value can be attained for many combinations of compacted density and water contents (Daniels 1990). Dry density/water combinations that result in compaction at a relatively high degree of saturation are most effective in minimizing permeability for a given soil.

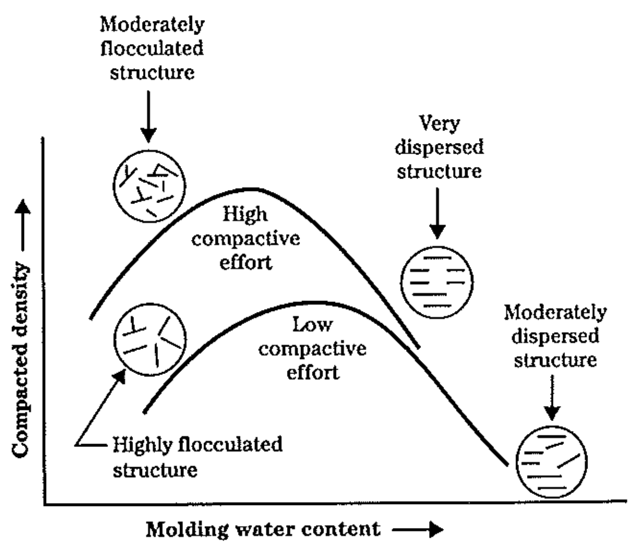
(2) Percent saturation criteria

A given value of permeability may be attained at any number of combinations of dry density and molding water content. Generally, for any given value of dry density, a lower permeability is attained if soils are compacted wet of optimum. However, many combinations of dry density and molding water content result in acceptably low permeability if the degree of saturation is high enough and a certain lower bound dry density value is met. For instance, a soil compacted at 90 percent of maximum Standard Proctor dry density at a water content 2 percent wet of optimum may have about the same permeability as a soil compacted to 95 percent of maximum Standard Proctor dry density at a water content equal to optimum water content.

Daniels (1990) describes a method of specifying combinations of dry density and water content to meet a certain permeability goal. Extensive testing may be required to establish the range of acceptable dry density and molding water content for a particular sample or site using this method. To limit soil mechanics testing complexity, generally no more than three combinations of dry density and placement water content are investigated to arrive at a design recommendation. More detailed analyses are usually reserved for large sanitary landfills or hazardous waste sites.

Figure 10D–4 shows how a different structure results between soils compacted wet of optimum and those compacted dry of optimum water content. It also illustrates that soils compacted with a higher compactive effort or energy have a different structure than those compacted with low energy.

Figure 10D–4 Effect of water content and compactive effort on remolding of soil structure in clays (from Lambe 1958)



(h) Energy level of compaction

The relationship of maximum dry density and optimum water content varies with the compactive energy used to compact a soil. Higher compactive energy results in higher values of maximum dry unit weight and lower values of optimum water content. Lower compactive energy results in lower values of maximum dry unit weight and higher values of optimum water content. Because optimum water content varies with the energy used in compaction, its nomenclature can be misleading. The optimum water content of a soil is actually for the particular energy used in the test to measure it.

Compactive energy is a function of the weight of the roller used, the thickness of the lift, and the number of passes of the roller over each lift. Rollers must be heavy enough to cause the teeth on the roller to penetrate or almost penetrate the compacted lift. Enough passes must be used to attain coverage and break up any clods. As such, additional passes cannot be used to compensate for rollers that are too light for the job.

Roller size is often specified in terms of contact pressure exerted by the feet on tamping rollers. Light rollers have contact pressures less than 200 pounds per square inch, while heavy rollers have contact pressures greater than 400 pounds per square inch.

Limited data are available for various sizes of equipment to correlate the number of passes required to attain different degrees of compaction. Typically, from 4 to 8 passes of a tamping roller with feet contact pressures of 200 to 400 pounds per square inch are required to attain degrees of compaction of from 90 to 100 percent of maximum Standard Proctor dry density. However, this may vary widely with the soil type and weight of roller used. Specific site testing should be used when possible.

(i) Equipment considerations

(1) Size and shape of teeth on roller

Tamping rollers should have teeth that protrude an appreciable distance from the drum surface, as the older style sheepsfoot rollers do. The newer types of tamping rollers have square pads that do not protrude far from the drum surface. They appear less desirable than the older style rollers because less bonding and destruction of clay clods probably result.

(2) Total weight of roller

To attain penetration of the specified loose lift, the roller weight must be appropriate to the specified thickness and the shape of the roller teeth. Many modern rollers have contact pressures that are too great to compact soils appreciably wet of optimum water content. When the specified compaction water content is approaching 90 percent theoretical saturation at the specified dry density, lighter rollers are essential. Permeability of clays is minimized by compaction at water contents wet of optimum.

(3) Speed of operation

Heavy rollers operated at excessive speed can shear the soil lifts being compacted. This can result in higher permeability. Close inspection of construction operations should indicate when this problem occurs, and adjustments to equipment or the mode of operation should then be made.

(4) Vibratory versus nonvibratory

Vibratory type tamping rollers appear to have few advantages in constructing clay liners. These rollers may be counterproductive when the base soil is saturated and lower in plasticity because the vibration can induce pore pressures in the underlying base soil and create free water. Smooth-wheeled vibratory rollers should never be used in compacting clay liners. They are suitable only for relatively clean, coarse-grained soil.

Design and construction of bentonite clay liners

Some waste impoundment sites may not have soils within a practical distance that are suitable to serve as a clay liner. When this is the situation, there are generally two alternatives:

- Construct a synthetic liner.
- Import bentonite for treating the in situ soil on the sides and bottom of the impoundment.

(a) Bentonite type and quality

Bentonite is a volcanic clay that swells to about 15 times its original volume when placed in water. There are a number of bentonite suppliers, primarily located in the Western States. A sodium type bentonite should be used for constructing bentonite treated liners for waste impoundments. Another type of bentonite, calcium bentonite, should not be used. For bentonite to be suitable for use in constructing a liner for a waste impoundment, it must have two important qualities. One quality is that it possess a minimum level of activity or the ability to swell. The other quality bentonite must possess is an appropriate fineness.

The two primary ways of determining if a bentonite under consideration has an adequate level of activity are:

- Determine its level of activity based on its Atterberg limit values as determined in a soil testing laboratory. High quality sodium Wyoming bentonite has LL values greater than 600 and PI values greater than 550.
- Determine its level of activity based on a test of its free swell. Bentonite should have a free swell of at least 22 mL as measured by ASTM Standard Test Method D 5890. A brief summary of the free swell test follows. However, the ASTM Standard Test Method should be reviewed for detailed instructions on performing the test.
  - — Prepare a sample for testing that consists of material from the total sample that is finer than a #100 sieve with at least 65 percent finer than a #200 sieve.
  - — Add 90 mL of distilled water to a 100 mL graduated cylinder.
  - — Add 2 grams of bentonite in small increments to the cylinder. The bentonite will sink to the bottom of the cylinder and swell as it hydrates.
  - — Rinse any particles adhering to the sides of the cylinder into water while raising the water volume to the 100 mL mark.
  - — After 2 hours, inspect the hydrating bentonite column for trapped air or water separation in the column. If present, gently tip the cylinder at a 45 degree angle and roll slowly to homogenize the settled bentonite mass.
  - — After 16 hours from the time the last of sample was added to the cylinder, record the volume level in milliliters at the top of the settled bentonite. Record the volume of free swell, for example, 22 milliliters free swell in 16 hours.

Bentonite is furnished in a wide range of particle sizes for different uses including clarification of wine. Fineness provided by the bentonite industry ranges from very finely ground, almost like face powder, to a granular form, with particles about the size of a #40 sieve. Laboratory permeability tests have shown that even though the same quality of bentonite is applied at the same volumetric rate to a sample, a dramatic difference in the resulting permeability can occur between a fine and a coarse bentonite. It is important to specify the same quality and fineness as was used by the soils laboratory for the permeability tests to arrive at recommendations. An appropriate fineness for use in treating liners for waste impoundment can be obtained specifying an acceptable bentonite by supplier and designation. An example specification is Wyo Ben type Envirogel 200, CETCO type BS-1, or equivalent.

(b) Design details for bentonite liner

The criteria given in NRCS Practice Standard, 521C, Pond Sealing or Lining, Bentonite Sealant, requires a 4-inch-thick bentonite treated layer for water depths in the impoundment of 8 feet or less. The criteria infers that a thicker liner should be used for deeper impoundments. Although not directly stated in the standard, the thickness of the liner should be proportional to the head of water in the impoundment for depths of more than 8 feet. For waste impoundment liners, a minimum thickness liner of 6 inches is recommended for constructibility.

The design procedure using the laboratory permeability k value of treated samples is the preferred method to arrive at a required liner thickness. This procedure uses the depth of liquid in the impoundment, the k value of the treated soil, and an allowable seepage rate. The procedure is covered in the examples in this appendix. The calculated thickness is recommended unless it is less than 6 inches; then, the minimum thickness liner would be used regardless.

Consideration should be given to providing a soil cover over the bentonite treated compacted liner in waste impoundments. There are several reasons why a soil cover should be provided:

- The potential for desiccation cracking of the liner on the side slopes may occur during periods when the impoundment is drawn down for waste utilization or sludge removal. Desiccation cracking would significantly change the permeability of the liner. Rewetting generally does not completely heal the cracks.
- The potential for erosion of the thin bentonite treated liner that could occur during periods when the impoundment has been drawn down. Rilling due to rainfall on the exposed slopes can also seriously impair the water tightness of the liner.
- Over excavation by mechanical equipment during sludge removal. A minimum thickness of 6 inches measured normal to the slope and bottom is recommended for a protective cover. The protective cover should be compacted to reduce its erodibility.

(c) Construction specifications for bentonite liner

The best equipment for compacting bentonite treated liners is rubber-tired or smooth wheeled steel rollers, or crawler tractor treads. Practice Standard 521-C specifies that for mixed layers, the material shall be thoroughly mixed to the specified depth with disk, rototiller, or similar equipment. In addition, intimate mixing of the bentonite is essential to constructing an effective liner. If a standard disk is used, several passes should be specified. A high speed rototiller as is used on lime treated earthfills is the best method of obtaining the desired mix. A minimum of two passes of the equipment is recommended to assure good mixing.

Another construction consideration is the moisture condition of the subgrade into which the bentonite is to be mixed. Unless the subgrade is somewhat dry, the bentonite will most likely ball up and be difficult to thoroughly mix with the underlying soils. Ideally, bentonite should be spread on a relatively dry subbase, mixed thoroughly with the native soil, then watered and compacted.

A sheepsfoot or tamping type of roller should not be used for compacting a bentonite treated liner. Dimples in the surface developed by these rollers cause the effective liner thickness to be significantly less than planned.

Other construction considerations are also important. For some equipment, tearing of the liner during compaction can occur on slopes even as flat as 3:1. On the other hand, compacting along rather than up and down the slopes could be difficult on slopes as steep as 3:1. For some sites, slopes as flat as 3.5:1 or 4:1 should be considered for this factor alone.

A design may occasionally call for a liner thickness of more than 6 inches. A 6-inch-thick liner can probably be satisfactorily constructed in one lift, mixing in the required amount of bentonite to a 9-inch-thick loose depth, and then compacting it to the suggested 6 inches. Thicker liners should be constructed in multiple lifts, with the final compacted thickness of each lift being no greater than 6 inches. For instance, to construct an 8-inch-thick liner, use two 4-inch-thick compacted lifts.

Design and construction of clay liners treated with soil dispersants

The *Permeability of soils* section cautions that soils in Group III containing high amounts of calcium may be more permeable than indicated by the percent fines and PI values. Group III soils predominated by calcium require some type of treatment to serve as an acceptable liner. The most prevalent method of treatment to reduce the permeability of these soils is use of a soil dispersant additive containing sodium in some form.

(a) Types of dispersants

The dispersants most commonly used to treat high calcium clays are soda ash (Na_2CO_3), TSPP (tetrasodium pyrophosphate), and STPP (sodium tetra phosphate). Common salt (NaCl) has been used, but it is considered less long-lasting than the other chemicals. All these dispersants may be obtained from commercial suppliers. NRCS experience has shown that usually about twice as much soda ash is required to effectively treat a given clay than the polyphosphates. However, because soda ash may be less than half as expensive, it may be the most economical choice in many applications.

(b) Design details for dispersant treated clay liner

The criteria given in NRCS Practice Standard, 521B, Pond Sealing or Lining, Soil Dispersant, requires a 6-inch-thick dispersant treated layer for water depths in the impoundment of 8 feet or less. The criteria infers that a thicker liner should be used for deeper impoundments. Although not directly stated in the standard, the thickness of the liner should be proportional to the head of water in the impoundment for depths of more than 8 feet. To illustrate, for a liquid depth of 12 feet, a minimum liner thickness of one and one-half the minimum thickness should be used. For waste impoundment liners, a minimum thickness liner of 6 inches is recommended for constructibility.

Design procedures using the laboratory permeability k value of treated samples are the preferred method to arrive at a required liner thickness, using the depth of liquid in the impoundment, the k value of the treated soil, and an allowable seepage rate. Laboratories should be requested to perform trials with various amounts of a given additive to determine the most economical design. This procedure is covered in the examples in this appendix. The calculated thickness is recommended unless it is less than 6 inches, then the minimum thickness liner would be used regardless.

For planning purposes, the information given in NRCS Practice Standard, 521B, Pond Sealing or Lining, Soil Dispersant, may be used to determine approximate amounts of dispersants that will be required. Preliminary estimates given for soda ash are 10 to 20 pounds per 100 square feet (mixed into a compacted 6-inch layer). For STPP or TSPP, 5 to 10 pounds per 100 square feet is recommended.

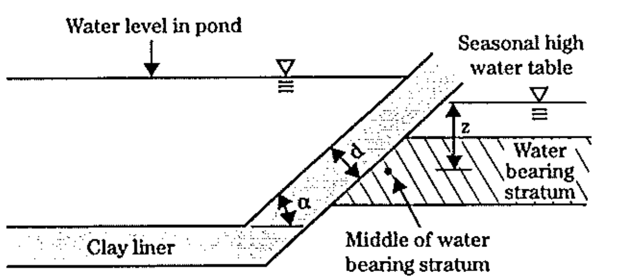
(c) Construction specifications for dispersant treated clay liner

The best equipment for compacting clays treated with dispersants is a sheepsfoot or tamping type of roller. Practice Standard 521-B specifies that the material shall be thoroughly mixed to the specified depth with disk, rototiller, or similar equipment. Because small quantities of soil dispersants are commonly used, intimate mixing of the dispersants is essential to constructing an effective liner. If a standard disk is used, several passes should be specified. A high speed rototiller as is used on lime treated earthfills is the best method of obtaining the desired mix. A minimum of two passes of the equipment is recommended to assure good mixing.

Other construction considerations are also important. For some equipment, tearing of the liner during compaction can occur on slopes even as flat as 3:1. On the other hand, compacting along rather than up and down the slopes could be difficult on slopes as steep as 3:1. For some sites, slopes as flat as 3.5:1 or 4:1 should be considered for this factor alone.

A design may occasionally call for a liner thickness greater than 6 inches. A 6-inch-thick liner generally can be satisfactorily constructed in one lift by mixing in the required amount of soil dispersant to a 9-inch-thick loose depth and then compacting it to the 6 inches. Thicker liners should be constructed in multiple lifts, with the final compacted thickness of each lift being no greater than 6 inches. For instance, to construct an 8-inch-thick liner, use two 4-inch thick compacted lifts.

Figure 10D–5 Uplift calculations for high water table (from Oakley 1987)



Uplift pressures beneath clay blankets

In some situations a clay blanket is subject to uplift pressure from a seasonal high water table in the foundation soil behind or beneath the clay liner. The uplift pressure in some cases can exceed the weight of the clay liner, and failure in the clay blanket can occur. This problem can occur particularly during the period before the waste impoundment is filled and during periods when the impoundment may be emptied for maintenance and cleaning. Figure 10D–5 illustrates the parameters involved in calculating uplift pressures for a clay blanket. The most critical condition for analysis typically occurs when the pond is emptied. Thicker blankets may be needed to attain satisfactory safety factors.

The safety factor against uplift is the ratio of the pressure exerted by a column of soil to the pressure of the ground water under the liner. It is given by the equation:

$$FS = \frac{\gamma_{sat} \times d \times \cos(\alpha)}{z \times \gamma_{water}}$$

where:

- d = Thickness of liner, measured normal to the slope
- α = Slope angle
- γ_w = Unit weight or density of water
- γ_{sat} = Saturated unit weight of clay liner
- z = Vertical distance from middle of clay liner to the seasonal high water table

A safety factor of at least 1.1 should be attained. The safety factor can be increased by using a thicker blanket or providing some means of intercepting the ground water gradient and lowering the potential head behind the blanket.

Soil mechanics testing

(a) Sample size needed for testing

Laboratory soil testing may be required by regulations for design, or a designer may not be comfortable relying on correlated permeability test values. The NRCS National Soil Mechanics Center Laboratories have equipment and the ability to perform the necessary tests. Similar testing is also available at many commercial labs. Allow 3 to 4 weeks for obtaining gradation and Atterberg limits, and 6 to 8 weeks for permeability and sealing tests results. Contact the labs for more detailed information on documentation needed and for procedures for submitting samples.

Sample size based on percent gravel content for gradation analysis and Atterberg Limit only should be as follows:

Estimated gravel content of the sample 1/ (%)	Sample moist weight (lb)
0 – 10	5
10 – 50	20
> 50	40

1/ The sample includes the gravel plus the soil material that passes the No. 4 sieve (approx. 1/4 inch mesh).

Sample size based on percent gravel content for gradation analysis, Atterberg Limits, and for compaction and permeability testing should be as follows:

Estimated gravel content of the sample 1/ (%)	Sample moist weight (lb)
0 – 10	50
10 – 50	75
> 50	100

1/ The sample includes the gravel plus the soil material that passes the No. 4 sieve (approx. 1/4 inch mesh).

If designs rely on a minimum degree of compaction and water content to achieve stated permeability goals in a clay liner, testing of the clay liner during construction may be advisable to verify that design goals have been achieved. Field density and water content measurements are routinely made using procedures shown in NEH Part 646 (section 19), Construction Inspection.

(b) Factors in laboratory permeability testing for clay liners

Laboratory permeability testing is often used for design of compacted clay liners. The following sections describe factors that are important in laboratory testing and in writing construction specifications. However, the clay liner must be constructed properly for these laboratory tests to reflect accurately the actual permeability of the completed liner. Previous sections discuss many additional construction considerations.

(1) Placement dry density or degree of compaction

For a given soil, many different combinations of dry density and molding water content can result in an acceptable permeability value. For a given value of molding water content, increasing the degree of compaction will usually reduce the permeability. Degree of compaction is the percentage of the soil's maximum Standard Proctor dry density. Specimens remolded to a higher density, at the same water content, will have a lower permeability than specimens remolded to a lower density. The following table summarizes test data from an NRCS laboratory that illustrates this:

Percent maximum γ_d	Water content referenced to optimum	k value (cm/s)
90.1	Optimum + 1.7 %	9.6×10^{-6}
95.1	Optimum + 1.7 %	3.4×10^{-6}
100.1	Optimum + 1.7 %	6.0×10^{-8}

Compacting a soil to a higher degree is usually more economical than including additives, if compaction achieves the required permeability. However, some soils cannot be compacted sufficiently to create a satisfactorily low permeability. Then, additives are the only choice. Both the cost of additives and the cost of application must be considered in comparisons. One must also include the cost of quality control in verifying a higher degree of compaction when comparing this alternative.

The minimum degree of compaction that one should consider for clay liners is 90 percent. Usually, this degree of compaction is easily obtained if thin lifts are used and the water content is in the proper range. This degree of compaction may not require specialized compaction equipment for many soils.

The maximum degree of compaction that one should usually consider for clay liners in NRCS designs is 100 percent of Standard Proctor dry density. This degree of compaction is achievable, but for clay soils, probably only by using sheepsfoot or tamping rollers. For a bentonite treated liner, pneumatic rollers may be preferable. While achieving a degree of compaction higher than 100 percent of Standard Proctor dry density is possible, specifying higher values is not common. An intermediate degree of compaction that is commonly specified is 95 percent of maximum Standard Proctor dry density.

(2) Molding water content

Usually, for a given value of dry density or degree of compaction, increasing the molding water content will reduce the permeability. The following summary of tests performed at an NRCS Laboratory illustrates this point:

Percent maximum γ_d	Water content + or - optimum	k value cm/s
95	Optimum - 2 %	4.0×10^{-4}
95	Optimum	5.0×10^{-5}
95	Optimum + 2 %	9.0×10^{-6}

The in situ water content of borrow soils should be carefully considered in a preliminary design for a compacted clay liner. One should know what construction equipment is commonly available. If the in situ water content of borrow soils is high, compacting soils to a high degree may be impractical. If the in situ water content of borrow soils is low, it may be easier to compact the soils to a higher degree and require less water to be added during construction.

A previous section of appendix 10D includes steps for determining the upper water content at which a given dry density is achievable. The highest placement water content that one should consider for a given degree of compaction, or dry density, corresponds to 90 to 95 percent of theoretical saturated water content. Compaction of soils results primarily from expulsion of air from the soil voids. Expelling the last 5 to 10 percent of air in soils with significant fines content by compaction is difficult. Even repeated applications of energy seldom result in increased degrees of saturation when soils are very wet. Example 10D-6 illustrates calculations.

Most clay liners should be compacted at optimum water content or wetter to minimize permeability. However, for high degrees of compaction, allowing placement at 1 to 2 percent dry of optimum may be necessary to allow some range in placement water contents and give flexibility to contractors' operations. Laboratory tests should usually consider the least favorable conditions in evaluating permeability for conservatism.

It must be possible to attain the required degree of compaction over a range of placement water contents. If the specified minimum placement water content is near 90 percent saturation at the required dry density, there will be little flexibility in obtaining the required dry density during construction. Specifications should enable the desired densification to be obtained within a range of 2 to 4 percent in placement water contents. Specifications cannot require both a high degree of compaction and a high placement water content and be practical. Example 10D-5 illustrates calculations.

(3) Soil Additives - Bentonite

It may be obvious for a given soil that an acceptably low permeability cannot be obtained by compaction alone. An example is a sand with relatively low fines content. For other soils, usually clays with a high calcium content, it may not be immediately obvious that compaction alone will be inadequate. For either case, if soil additives are needed, the following guidelines should be considered.

- Sodium bentonite should be the additive selected to be investigated if the soil has a low percentage of fines, less than 50 percent, or, if the soil has low plasticity fines (PI less than about 7). NRCS Conservation Practice Standard 521C suggests that bentonite should be used for soils with less than 50 percent fines. The Standard shows preliminary application rates, as follows:

Soil type	Application rate, lb/ft^2
Silty sand	1.5 - 2.0
Clean sand	2.0 - 2.5

The rate given is based on the bentonite being mixed and compacted into a finished layer that is 4 inches thick. Then, a volumetric rate, in pounds per cubic feet, would be triple the rate given in the table.

- The quality and fineness of bentonite used for laboratory permeability testing is important. Previous sections of appendix 10D also discuss quality of bentonite. The bentonite used for laboratory tests should be comparable to that which will be used in construction. Bentonite processors furnish bentonite in a range of particle sizes, ranging from very finely ground, with most of the particles finer than the #200 sieve, to granular bentonite, with most of the particles larger than about the #40 sieve. NRCS laboratories have found a significant difference in permeability between specimens prepared using the same application rate of the fine compared to the coarse bentonites, for some soils.
- Each grade of bentonite has its advantages. The very finely ground bentonite usually is more effective in reducing permeability. However, the material is prone to dusty conditions during construction, and may ball up when applied to a wet sub-grade. The coarsely ground bentonite is easier to spread and mix, but may require a higher application rate to achieve a given target permeability.
- Permeability tests to evaluate bentonite should assumine a relatively low degree of compaction, usually no more than 95 percent of maximum Standard Proctor dry density. At least 2 or 3 tests should be requested, to determine the minimum quantity of bentonite required to obtain the desired permeability. A range of bentonite application rates of from 0.5 to 2.5 pounds per square foot (mixed into a compacted 4 inch layer), equivalent to1.5 to 7.5 pounds per compacted cubic foot, should be considered.
- The following example test results were obtained in a test on a relatively clean sand in an NRCS laboratory

Test γ_d % max	Test w % ref. to opt.	Additive type	Additive rate lb/ft²	k cm/s
90	Opt + 1.5 %	Fine Bentonite	0.5	3.5×10^{-4}
90	Opt. + 1.8 %	"	1.0	5.5×10^{-7}
90.1	Opt. + 2.0 %	"	1.5	9.6×10^{-8}

(4) Soil additives - dispersants.

A soil dispersant should be selected for the additive to be investigated if the soil has more than about 50 percent fines, if the soil has at least 15 percent clay content (percent finer than 2 microns), and has a PI value of 7 or higher. Soil dispersants are usually considered when previous tests or experience in an area show that compaction alone will not produce a satisfactorily low permeability. The two preferred types of soil dispersant chemicals are soda ash (Na_2CO_3) and sodium polyphosphate (STPP or TSPP). Recommended preliminary application rates are as follows:

Dispersant type	Application rate, lb/100 ft²
Soda ash	10–20
Polyphosphates	5–10

- The stated application rate is based on the given amount of dispersant being mixed and compacted into a finished layer that is 6 inches thick. Then, a rate, in pounds per cubic feet, would be double the rate given in the above table.
- Either soda ash or polyphosphates are most commonly used. About twice as much soda ash is required to produce a given permeability, other factors being equal, than polyphosphates. However, if the product cost of soda ash is less than half that of polyphosphates, or it is more readily available, then soda ash should be selected. The cost of application and incorporating the additive into the soil should be the same for both chemicals. NRCS laboratories have supplies of either of these soil dispersants, and it is not necessary to provide supplies for testing when this option is being explored.
- Permeability tests using soil dispersants should be performed for a range of assumed degrees of compaction, probably in the range of 90 to 100 percent of maximum Standard Proctor dry density. At least two or three tests should be requested, to determine the minimum quantity of dispersant required to obtain the desired permeability. A range of dispersant application rates of from 5 to 20 pounds per 100 square feet (mixed into a compacted 6-inch layer), or from 0.1 to 0.4 pounds per compacted cubic foot, should be considered.

- The following example test results were obtained in a test on a CL soil in an NRCS laboratory

Test γ_d % max	Test w % ref. to opt.	Additive type	Additive rate lb/ft²	k cm/s
94.8	Opt. + 2.0 %	None	**	4.9×10^{-6}
99.9	Opt. + 2.0 %	None	**	1.6×10^{-6}
95.0	Opt. + 2.0 %	Soda Ash	10	2.5×10^{-6}
95.0	Opt. + 2.0 %	Soda Ash	15	9.5×10^{-8}

(5) Construction quality control and procedures

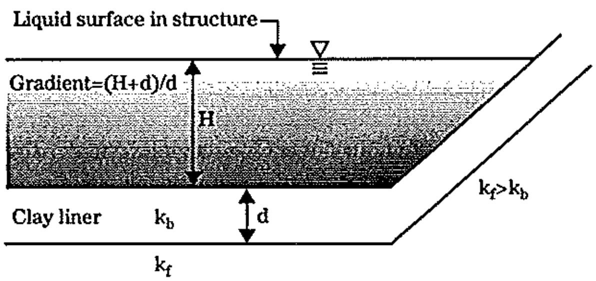
One should consider which construction equipment and methods are commonly available when selecting combinations of dry density and molding water in the design of clay liners. Some of these considerations are summarized as follows. The discussion specifically applies to Standard Proctor compaction (ASTM D698). Different guidelines would apply to designs using Modified Proctor (ASTM D1557) compaction tests.

- It may be difficult to obtain a degree of compaction greater than about 90 percent for many clay soils unless a sheepsfoot or tamping type roller, together with thin lifts is employed. If laboratory tests show that 95 or 100 percent of Proctor dry density is required to obtain a satisfactorily low permeability, plans should require this equipment for the clay liner construction.
- It will usually be more economical to specify a lower degree of compaction and a higher water content, unless the in situ water content of borrow soils is low, and water must be incorporated prior to compaction. If the in situ water content of borrow soils is excessive, it may be impossible to achieve higher degrees of compaction, as detailed in previous sections.
- The field quality control testing effort required to verify that soils are compacted to a higher degree must be considered. Achieving 90 percent of maximum Standard Proctor dry density is relatively easily accomplished, and observations of construction operations may be sufficient verification. Using thin lifts and thorough coverage of the equipment usually results in this degree of compaction. Higher degrees of compaction, greater than 90 percent, are more difficult to achieve, and field quality control testing probably should be a part of documentation. Qualified personnel and appropriate testing equipment are necessary for this effort.
- In the absence of previous experience in an area, the following initial trials are suggested for laboratory permeability tests. Some of these trials may not be necessary, or other trials should be assigned if factors dictate.

Degree of compaction	Placement water content ref. to opt.
90	Opt. + 3
95	Opt. + 2
100	Opt. or Opt. + 1

Exhibit 10D–1 Derivation of equations

Definition sketch for clay liner in waste storage pond or treatment lagoon



where:

H = Head of waste liquid in waste impoundment
k_f = Permeability of foundation
d = Thickness of liner
k_b = Permeability of liner

Derivation of equation for calculating required thickness of liner

Using the equation for specific discharge, v

$$v = \frac{[k \times (H + d)]}{d} \qquad [8a]$$

The units for specific discharge in the English system are cubic feet per square foot per day. The coefficient of permeability, k, also has units of cubic feet per square foot per day. These units are usually simplified to units of feet per day. Using metric units, specific discharge and the coefficient of permeability are generally expressed in cubic centimeters per square centimeter per second, simplified to centimeters per second. Units for H and d cancel, but the same basic units should be used as used for permeability to reduce confusion (either feet or centimeters).

Then:

$$v = \frac{[(k \times H) + (k \times d)]}{d} \qquad [8b]$$

$$v \times d = (k \times H) + (k \times d) \qquad [8c]$$

$$(v \times d) - (k \times d) = k \times H \qquad [8d]$$

$$d \times (v - k) = k \times H \qquad [8e]$$

$$d = \frac{(k \times H)}{(v - k)} \qquad [8f]$$

Exhibit 10D–1 Derivation of equations—Continued

Derivation of equation for calculating required permeability of liner

To solve for the required k value, given an allowable specific discharge, a liner thickness, and a height of waste liquid in the impoundment, begin with equation 8d:

$$(v \times d) - (k \times d) = k \times H \qquad [8d]$$

$$(v \times d) = (k \times H) + (k \times d) \qquad [9b]$$

$$v \times d = k(H + d) \qquad [9c]$$

$$k = \frac{v \times d}{(H + d)} \qquad [9d]$$

Example 10D–1 Example calculations for required minimum thickness of compacted soil liner

Given: Site design has resulted in a required depth of waste liquid, H, in the constructed waste impoundment of 12 feet. A soil sample was obtained and submitted to a soil mechanics laboratory for testing. A permeability test on a sample of proposed clay liner soil resulted in a permeability value of 3.0×10^{-7} centimeters per second (0.00085 ft/d) for soils compacted to 95 percent of maximum Standard Proctor dry density. Another test on a sample compacted to 90 percent of maximum density resulted in a measured k value of 6×10^{-6} centimeters per second (0.017 ft/d).

Assume: Allowable specific discharge of 1×10^{-5} centimeters per second (0.028 ft/d) is satisfactory because manure sealing will produce an order of magnitude reduction in permeability.

Solution:

Step 1: Design a liner assuming soils are to be compacted to 95 percent of maximum Standard Proctor dry density. It is given that the k value at this density is 0.00085 foot per day. Calculate the required minimum thickness of compacted liner as follows:

The equation for required d is:

$$d = \frac{k \times H}{v - k}$$

Using English system units, substituting the given values for H and k, assuming an allowable specific discharge, v, of 0.028 foot per day, then

$$d = \frac{0.00085 \times 12}{0.028 - 0.00085}$$
$$d = 0.38 \text{ ft.}$$

A 1-foot-thick minimum thickness is suggested for a soil liner because thinner clay liners are difficult to construct with confidence.

Step 2: For the case of the liner being compacted to about 90 percent of maximum density, the calculated required d, using a given value for k at this density of 0.017 foot per day and the given value of H of 12 feet, is:

$$d = \frac{k \times H}{v - k}$$
$$d = \frac{0.017 \times 12}{0.028 - 0.017}$$
$$d = 18.5 \text{ ft}$$

Conclusion: The final calculation shows that the design based on 90 percent degree of compaction results in a liner thickness that is impractical. Other options could be explored for reducing the permeability including compaction at higher water contents. Including provisions for extra effort in attaining the required 95 percent of maximum density or adding extra water in compaction generally is far more economical than using thick liners. Sheepsfoot rollers would probably be required to attain 95 percent of maximum Standard Proctor dry density for a clay soil.

Example 10D–2 Example calculations for required minimum thickness of compacted soil liner

Given: Site design has resulted in a required depth of waste liquid, H, in the constructed waste impoundment of 10 feet. A soil sample was obtained and submitted to a soil mechanics laboratory for testing. Based on Atterberg limits and gradation analyses, the soil to be used for a liner is in Group III. Based on guidance following table 10D–2, a soil in Group III if compacted to at least 90 percent of maximum dry density will probably have a permeability value of 0.0028 foot per day or less. Assume that an allowable specific discharge of 0.028 foot per day is satisfactory.

Solution: Calculate the required minimum thickness of compacted liner assuming that the above information is accurate. The equation for required d is:

$$d = \frac{k \times H}{v - k}$$

Using English system units, then

$$d = \frac{0.0028 \times 10}{0.028 - 0.0028}$$

$$d = 1.2 \text{ ft}$$

A 1.2-foot minimum thickness would be used for this liner.

Example 10D–3 Example calculations for required minimum thickness of compacted soil liner

Given: Site design has resulted in a required depth of waste liquid, H, in the constructed waste storage pond impoundment of 9 feet. A soil sample was obtained and submitted to a soil mechanics laboratory for testing. Based on Atterberg limits and gradation analyses, the soil to be used for a liner is in Group I. Laboratory tests show that if bentonite is added to the soil at the rate of 3 pounds per square foot, mixed into a 4-inch-thick compacted layer, that a coefficient of permeability of 5.0×10^{-7} centimeters per second is achievable.

Determine: Minimum required thickness of the bentonite treated liner assuming that an allowable specific discharge of 0.028 foot per day is satisfactory.

Solution: Calculate the required minimum thickness of compacted liner.
Convert the stated coefficient of permeability of the liner to feet per day. The conversion from centimeters per second to feet per day is:

$$\frac{1\,\text{cm}}{\text{s}} \times \frac{86,400}{1\,\text{d}} \times \frac{1\,\text{ft}}{30.48\,\text{cm}} = 2,835\,\text{ft/d}$$

$$5 \times 10^{-7}\,\text{cm/s} \times 2,835 = 0.0014\,\text{ft/d}$$

The equation for required d is:

$$d = \frac{k \times H}{v - k}$$

Using English system units, then

$$d = \frac{0.0014 \times 9}{0.028 - 0.0014}$$

$$d = 0.47\,\text{ft}$$

Based on previous material, a 6-inch minimum thickness would be used for this liner, but only because it is a bentonite treated material. Otherwise, a compacted soil liner would require a minimum thickness of 1 foot.

Example 10D–4 Example calculations for required minimum thickness of compacted soil liner

Given: The information is the same as that for example 10D–3 except it is given that a particular policy or regulation does not permit taking credit for a 1 order of magnitude reduction in permeability for manure sealing. The assumed value for allowable specific discharge then becomes 1 x 10^{-6} centimeter per second, or 0.0028 foot per day. Assume the same permeability value as that in example 10D–3.

Solution: The equation for required d is:

$$d = \frac{k \times H}{v - k}$$

Using English system units, then

$$d = \frac{0.0014 \times 9}{0.0028 - 0.0014}$$

$$d = 9\,\text{ft}$$

Because this is an impractical design, the value of permeability that would be required to attain a more realistic design would be of interest. The above equation can be rearranged to solve for k, given values for specific discharge, H, and an assumed liner thickness. The rearranged equation is show as follows:

$$k = \frac{v \times d}{H + d}$$

If a realistic liner thickness of 1 foot is assumed, use this equation to determine the required coefficient of permeability for a bentonite/soil mixture.

$$k = \frac{1 \times 0.0028}{1 + 9}$$

$$k = 0.00028$$

A designer could then work with a soil testing laboratory to determine the amount of bentonite and the degree of compaction required to attain this k value

Example 10D-5 Example calculations for required minimum thickness of compacted soil liner

This example assumes that a soil to be used for constructing a clay liner has a maximum dry density of 113.0 pcf and an optimum water content of 14.5 percent. The specific gravity of the soil solids, Gs, is 2.68. Assume that the soil will be compacted to 90 percent of maximum Standard Proctor dry density. Determine the following:

(a) The minimum acceptable dry density

$$\gamma_{dmin} = 0.9 \times 113.0 \text{ pcf} = 101.7 \text{ pcf}$$

(b) The upper limit of water content at which a soil can be compacted to this dry density.

(1) First, calculate the saturated water content at this dry density:

$$w_{sat} = \left(\frac{\gamma_{water}}{\gamma_d} - \frac{1}{G_s} \right) \times 100$$

$$w_{sat} = \left(\frac{62.4}{101.7} - \frac{1}{2.68} \right) \times 100 = 24.0\%$$

(2) A good rule of thumb is that soils are difficult to compact if the water content exceeds 90 percent of the theoretical saturated water content. Determine the water content that is 90 percent of the saturated water content is 0.9 x 24.0 % = 21.6%.

(3) Then if soils in the borrow are much wetter than 21.6 % water content, it will be difficult to obtain the required compaction.

(c) Assume that permeability tests show the soil should be compacted at least at a water content 3 percent wet of optimum. Then, what is the minimum water content permissible, and, given the solution above, what is the range in practical placement water content for this situation.

(1) The minimum water content is 3 percent wet of optimum, and optimum water content is 14.5 percent, so the minimum acceptable water content is 17.5 percent. The wettest the soil can be compacted to the required degree is 21.6 percent from the previous step. Then, the range of water content within which the specifications can be met is from 17.5 to 21.6 percent, a range of about 4 percent. This gives adequate flexibility during construction. Similar computations for considering placement of the soil to 100 percent of maximum Standard Proctor dry density are as follows:

(2) The minimum required dry density is 100 percent of maximum dry density, which is 113.0 pcf, and the saturated water content, calculated with the equation above, at this density is 17.9 percent. The upper feasible placement water content is 90 percent of saturation, or 16.1 percent. If one is to allow a 3 percent spread in attainable placement water contents, the lowest water content would be about 13 percent, which is 1.5 percent dry of optimum. A lab permeability test should be performed at this dry density/water content to verify that an acceptably low permeability is attainable.

Example 10D-6 Example calculations for required minimum thickness of compacted soil liner

Given: The in situ water content of soils in the borrow is 22.0 percent. The soil has a maximum dry density of 113.0 pcf and an optimum water content of 14.5 percent. The specific gravity of soil solids, G_s, is 2.68. Determine whether it is feasible to compact the soils to at least 95 percent of maximum Standard Proctor dry density.

Solution: (a) Given the maximum Standard Proctor dry density of the soil is 113.0 pcf, the minimum acceptable dry density is then 0.95 x 113.0 pcf, or 107.4 pcf. To determine the upper feasible placement water content, use the rule of thumb that 90 percent degree of saturation is the wettest a soil can be reasonably compacted. The saturated water content of a soil is calculated from the following equation, using the given values of dry density and specific gravity of solids.

$$w_{sat}(\%) = \left(\frac{\gamma_{water}}{\gamma_d} - \frac{1}{G_s} \right) \times 100$$

$$w_{sat}(\%) = \left(\frac{62.4}{107.4} - \frac{1}{2.68} \right) \times 100 = 20.8\%$$

(b) The wettest you should consider compacting the soil is 90 percent of theoretical saturated water content, or 0.9 x 20.8, or 18.7 percent.

(c) Then, the in situ water content of the soils in the borrow area, given as 22.0 percent, is greater than the highest water content at which the required density can be obtained. To achieve the required compaction, the soils will probably have to be dried by about 22.0–18.7, or 3.3 percent.

(d) This amount of drying may be attainable by disking repeatedly during hot, dry weather for some soils, but, highly plastic soils may be more difficult to dry. In some cases, a site should be constructed only during dry weather or the borrow area should be drained several months prior to construction.

Summary

The reduction in soil permeability by manure sealing in waste storage ponds and treatment lagoons is well documented. However, for this phenomenon to produce acceptable low permeability requires the soils at grade to have a minimum clay content (percent finer than 2 microns). A minimum clay content of 15 percent is required for sealing to occur if manures are from monogastric animals, and a minimum clay content of 5 percent is required for sealing if manures are from ruminant animals.

Soils can be divided into four permeability groups based on their percent fines (minus #200 sieve) and plasticity index (PI). Soils in Group III and IV generally do not require a liner. Group I soils will generally require a liner. Soils in Group II will need permeability tests or other documentation to determine whether or not a liner is advisable.

Guidance is given on when to consider a liner. Four conditions are listed in which a liner should definitely be considered.

Recommended values for allowable specific discharge and minimum liner thickness are given. A methodology is presented to calculate a minimum blanket thickness based on design parameters.

Flexibility is built into the design process. The depth of the liquid, the permeability, and thickness of the soil liner can be varied to provide an acceptable specific discharge.

A method of documenting the design rationale for inclusion in the design file is provided.

A practical means for evaluating, in quantitative terms, the level of ground water protection that can be achieved with a soil liner is also provided.

The guidelines provided in this chapter result in a somewhat conservative, but reasonable level of protection to important ground water resources. This guidance covers an area where uncertainties may exist. Additional research may produce better information, and practice standards will be updated to reflect this state-of-the-art knowledge.

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