651.1080 Appendix 10D Geotechnical, Design, and Construction Guidelines

Appendix 10D Geotechnical, Design and Construction Guidelines

Introduction

Waste storage ponds and treatment lagoons are used in agricultural waste management systems to protect surface and ground water and as a component in a system for properly utilizing wastes. Seepage from these structures has the potential to pollute surface water and underground aquifers. The principal factors determining the potential for downward and/or lateral seepage of the stored wastes are the:

- permeability of the soil and bedrock horizons near the excavated limits of a constructed waste treatment lagoon or waste storage pond,
- depth of liquid in the pond that furnishes a driving hydraulic force to cause seepage
- thickness of low permeability horizons between the boundary of the lagoon bottom and sides and the distance to the aquifer or water table

Natural soils and bedrock near the excavated limits of waste treatment lagoons and waste storage ponds may have an inherently low permeability. In some cases, the thickness and low permeability of these materials restrict seepage from the structure to acceptable levels. In other cases, the seepage may be excessive when low permeability layers do not occur beneath the site. In some cases, special designs may be required to reduce seepage to acceptable levels.

In some circumstances, designers may consider whether seepage may be reduced from the introduction of manure solids into the reservoir. Physical, chemical, and biological processes can 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 also be beneficial in reducing seepage. Researchers have reported that, under some conditions, the seepage rates from ponds can be decreased by up to an order of magnitude (reduced 1/10th) within a year following filling of the waste storage pond or treatment lagoon with manure. Manure with higher solids content is more effective in reducing seepage than manure with fewer solids content. Research has shown that manure sealing only occurs when soils have a minimal clay content. A rule of thumb supported by some research is the manure sealing is not effective unless soils have at least 15 percent clay content for hog waste and 5 percent clay content for dairy waste. Manure sealing is not considered effective on relatively clean sands and gravels, and these soils always require a liner as discussed in following sections.

General design considerations

Seepage from animal waste storage ponds and treatment lagoons should be minimized to reduce the potential for degradation of the quality of ground water and surface water into which ground water may discharge. The structures must either be located in environments where natural formations limit seepage to acceptable limits, or special measures must be used in designs to limit the seepage to acceptable limits. This document contains information that should be considered in the planning, design, construction, and operation of agricultural waste management components including waste treatment lagoons and waste storage ponds. This document also contains information on designs of compacted clay liners, improvement of soils with additives such as bentonite and soil dispersants, design of geosynthetic liners, composite liners such as geosynthetic clay liners, and a brief discussion of concrete liners.

Progressive design

Designs for waste storage ponds and treatment lagoons should use the least costly alternative design that will accomplish the design goals. Following is a listing of progressively complex and expensive designs related to limiting seepage from these structures. These design concepts should generally be considered in the order listed to provide the most economical yet effective design of these structures. The following descriptions cover details on design and installation of these individual design measures.

- The least expensive and least complex design is to locate a waste storage pond in soils and/or bedrock horizons that have a naturally low permeability and horizons that are of sufficient thickness to reduce seepage to acceptable levels. The site is also located where the distance to the water table conforms to requirements of any applicable regulations.
- If the soils or bedrock at the boundaries of the pond are not adequately low in permeability or thickness to limit seepage to acceptable levels, a liner may be constructed using various techniques. The constructed liner then has sufficiently low permeability and is thick enough to limit seepage to acceptable levels. The liner may be constructed of imported clay, clay obtained from the excavation of the pond, or by using additives or amendments to reduce the permeability of the *in situ* soils.
- A synthetic liner may be used to line the impoundment to reduce seepage to acceptable levels. Various types of synthetic materials including HDPE, LLDPE, EPDM, geosynthetic clay liners, and many others have been used.
- A liner may be constructed of concrete, or a concrete tank can be constructed above ground to store the wastes.

Designers must make preliminary cost comparisons of these progressively expensive but effective design options. A useful way of examining various alternatives for reducing seepage at an agricultural waste storage pond or lagoon is to review the unit costs. Many geomembrane suppliers may be able to provide rough cost estimates based on the size and locale of the site. In estimating the cost of a compacted clay liner (without additives which would increase the cost), one should evaluate the volume of compacted fill involved in a liner of given thickness. Table 10D–1 illustrates a cost comparison that could be useful.

Table 10D–1 Cost comparisons of design options

Thickness of compacted liner (ft)	Number of cubic yards of fill per square foot (yd^3)	Assumed cost of compacted fill, per cubic yard ($)	Unit cost of stated thickness liner ($/ft^2)
1.0	0.037037	3.00–5.00	0.11–0.19
1.5	0.055555	3.00–5.00	0.17–0.28
2.0	0.074074	3.00–5.00	0.22–0.37
3.0	0.111111	3.00–5.00	0.33–0.56

Soil properties

The permeability of soils at the boundary of a waste storage pond depends on several factors. The most important factors are the same as those used in soil classification systems such as the Unified Soil Classification System (USCS). The USCS groups soils into similar engineering behavior groups. The two most important factors that determine a soil's permeability are:

- The percentage of the sample which is finer than 0.075 millimeters, the No. 200 sieve size, expressed as a percent finer than the No. 200 sieve. The USCS has the following important categories of percentage fines:
  - Soils with less than 5 percent fines are the most permeable soils.
  - Soils with between 5 and 12 percent fines are next in permeability.
  - Soils with more than 12 percent fines but less than 50 percent fines are next in order of permeability.
  - Soils with 50 percent or more fines are the least permeable.

- The plasticity index, PI, of soils is another parameter that strongly correlates with permeability. When considered together with percent fines, a grouping of soils into four categories of permeability is possible. The following grouping of soils is based on experience of NRCS engineers. It may be used to classify soils at grade as an initial screening tool. Estimating permeability is difficult because so many factors determine the value for a soil. For *in situ* soils, the following additional factors, in addition to percent fines and PI, affect the permeability of the natural soils:
  - The dry density of the natural soil affects the permeability. Soils with lower dry densities have higher percentage of voids (porosity) than more dense soils.
  - Structure strongly affects permeability. Many clay soils, particularly those with PI values above 20, develop a blocky structure from desiccation. The blocky struc-

ture creates preferential flow paths that can cause soils to have an unexpectedly high permeability. Albrecht and Benson (2001) and Daniel and Wu (1993) discuss the effect of desiccation on the permeability of compacted clay liners.

– While not used in the USCS, the chemical composition of soils with clay content strongly affects permeability. The electrochemical makeup of a clay soil can strongly affect its permeability. Soils with a preponderance of calcium or magnesium ions on the clay particles often have a flocculated structure that causes the soils to be more permeable than expected based simply on percent fines and PI. Soils with a preponderance of sodium or potassium ions on the clay particles often have a dispersive structure that causes the soils to be less permeable than soils with similar values of percent fines and PI. The NRCS publication TR–28 describes this as follows:

In clay materials, permeability is also influenced to a large extent by the exchangeable ions present. If, for example, the Ca (calcium) ions in a montmorillonite are replaced by Na (sodium) ions, the permeability becomes many times less than its original value. The replacement with sodium ions reduces the permeability in several ways. For one thing, the sodium causes dispersion (disaggregation) reducing the effective particle size of the clay minerals. Another condition reducing permeability is the greater thickness of water adsorbed on the sodium-saturated montmorillonite surfaces which diminishes the effective pore diameter and retards the movement of fluid water.

– Alluvial soils may have thin laminations of silt or sand that cause them to have a much higher horizontal permeability than vertical permeability. This property is termed anisotropy and should be considered in flow net analyses of seepage.

– Other types of deposits may have structure resulting from their mode of deposition. Loess soils often have a high vertical permeability resulting from their structure. Glacial tills may contain fissures and cracks that cause them to have a permeability higher than might be expected based only on their density, percent fines and PI of the fines.

• The grouping of soils in table 10D–2 is based on the percent fines and Atterberg limits of the soils. Fines are those particles finer than the No. 200 sieve. Table 10D–3 is useful to correlate the Unified Soil Classification (USCS) groups to one of the four permeability groups.

Table 10D–2 Grouping of soils according to their estimated permeability. Group I soils are the most permeable, and soils in groups III and IV are the least permeable soils.

Group	Description
I	Soils that have less than 20 percent passing a No. 200 sieve and have a PI less than 5.
II	Soils that have 20 percent 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 percent or more passing a No. 200 sieve and have a PI of 16 to 30.
IV	Soils that have 20 percent or more passing a No. 200 sieve and have a PI of more than 30.

Table 10D–3 Unified classification versus soil permeability groups 1/

Unified Soil Classification System Group Name	Soil permeability group number and occurrence of USCS group in that soil			
	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 USCS.

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–4 shows an approximate range of estimated permeability values for each group of soils in table 10D–2. The ranges are wide because the classification system does not include important other factors such as the electrochemical nature of the clay in the soils. Two soils may have similar percentage fines and PI values but have very different permeability because of their different electrochemical makeup. The difference can easily be two orders of magnitude (a factor of 100). The most dramatic differences are between clays that have a predominance of sodium versus those with a preponderance of calcium or magnesium. High calcium soils are much higher in relative permeability than high sodium soils.

Table 10D–4 summarizes the experienced judgment of NRCS engineers and generally used empirical correlations of other engineers. The correlations are for *in situ* soils at medium density and without significant structure or chemical content that may affect the permeability strongly. Information shown in figure 10D–1 is also valuable in gaining insight into the probable permeability characteristics of various soil and rock types.

Table 10D–4 Grouping of soils according to their estimated permeability. Group I soils are the most permeable and soils in groups III and IV are the least permeable soils.

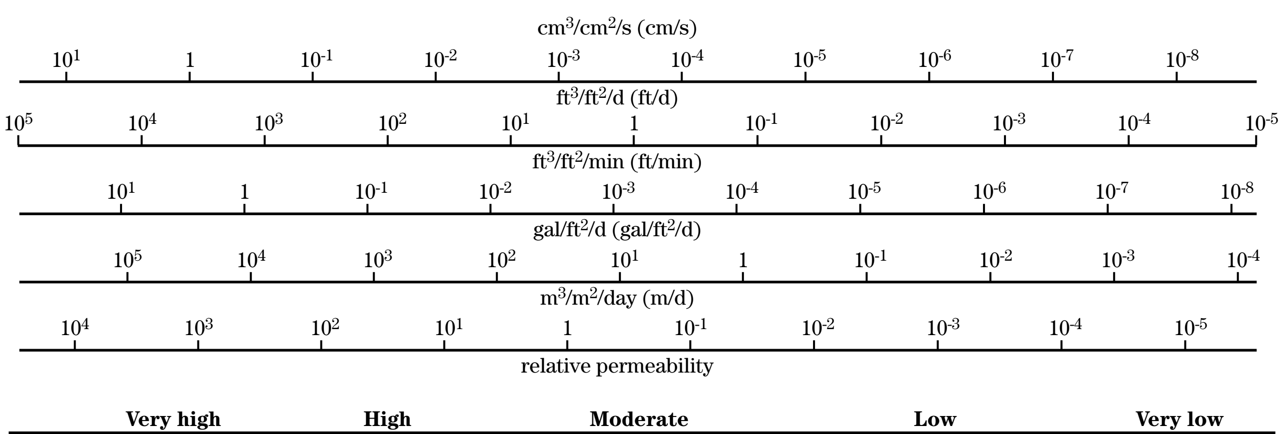
Group	Percent fines	PI	Range of permeability, cm/s	
			Low	High
I	<5	<5	3×10^{-3}	2
II	>20	<15	5×10^{-6}	5×10^{-4}
	<20	≥5		
III	>20	15≤PI≤30	5×10^{-8}	1×10^{-6}
IV	>20	>30	1×10^{-9}	1×10^{-7}

Some soils in groups III and IV may have a higher permeability than indicated in table 10D–4 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.

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. 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 liners 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.

Soils in group IV normally have a very low permeability. However, because of their sometimes blocky structure, caused by desiccation, 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. Soils with extensive desiccation cracks should be disked, watered, and recompacted to destroy the structure in the soils to 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.

Figure 10D–1 Permeability of various geologic material (from Freeze and Cherry 1979)



	Very high	High	Moderate	Low	Very low
			Representative materials		
Soil types	Clean gravel (GP)	Clean sand, clean sand and gravel mixes (GW, GP, SW, SP, SM)	Fine sand, silty sand and gravel mixes (SP, SM, GM, GW–GM, GP–GM, SW–SM, SP–SM)	Silt, clay, and sand-silt-clay mixes, organic silts, organic clays (GM, GC, SM, SC, MH, ML, ML–CL, OL, OH, GW–GC, GC–GM, SW-SC, SP–SC, SC–SM)	Massive clay, no soil joints or other macropores (CL, CH)
			Any soil mass with joints, cracks or other macroporosity		
Rock types		Cavernous and karst limestones and dolomites, permeable basalts	Limestones, dolomites, clean sandstones	Interbedded sandstones, siltstones, and shales	Most massive rocks, unfractured and unweathered
			Fractured igneous and metamorphic rocks		

In situ soils with acceptable permeability

For screening purposes, NRCS engineers have determined that if the boundaries of a planned pond are underlain on the sides and bottom both by a minimum of 2 feet of natural soil in permeability groups III or IV, the seepage from those ponds is generally low enough to cause no degradation of ground water. This depends on soils not having a flocculated structure. Unless state regulations or other requirements dictate a more conservative method of limiting seepage, it is the position of NRCS that 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.

However, this general statement only applies to sites with a moderate depth of liquid in the pond. Ponds with more than about 12 feet of liquid should be evaluated by more precise methods. If the permeability and thickness of horizons beneath a structure are known, more precise computations on the predicted seepage quantities are possible. In some cases, even though a site is underlain by 2 feet of naturally low permeability soil, a demonstrated acceptably low seepage rate satisfactory for some state requirements cannot be documented. In those cases, more precise testing and analyses are suggested. The accumulation of manure can provide a further decrease in the seepage rate of ponds by at least 1 order of magnitude as noted previously. If regulations permit considering this reduction, even lower predicted seepage can be assumed by designers.

Definition of pond liner

Compacted clay liner—Compacted clay liners are relatively impervious layers of compacted soil used to reduce seepage losses to an acceptable level. A liner for a waste impoundment can be constructed in several ways. When soil alone 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 a layer of the soils at the excavated grade by disking, watering, and compacting them to a thickness indicated by guidelines in following sections. Compaction is often the most economical method for constructing liners if suitable soils are available nearby or if soils excavated during construction of the pond can be reused to make a compacted liner. In some cases, naturally occurring soils at grade may be excavated, treated by disking and moisture conditioning, and compacted. 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. NRCS Conservation Practice Standard (CPS) 521D addresses general design guidance for compacted clay liners for ponds.

When the soil at the excavated grade is not in group III or IV, or is a group II soil that has been tested and found to demonstrate an unacceptably high permeability, several options are available as noted under progressive designs and described in more detail as follows.

Treat the soil at grade with bentonite or a soil dispersant—Designers must be aware of which amendment is appropriate for adding to specific soils at a site. In the past, bentonite has been inappropriately used to treat clay soils and soil dispersants have inappropriately been used to treat sands with a small clay content.

The following guidelines are helpful and should be closely followed.

- ***When to use bentonite***—Soils in groups I and II have unacceptably high permeability because they contain an insufficient quantity of clay or the clay in the soils is less active than required. A useful rule of thumb is that soils amenable for treatment with bentonite will have PI values less than 7, or they will have less than 30 percent finer than the No. 200 sieve, or both.

Bentonite is essentially a highly concentrated clay product that can be added in small quantities to a sand or slightly plastic silt to make it relatively low in permeability. (See the section, Design and construction of clay liners treated with soil bentonite). CPS 521C covers this practice, as well. 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.

- **When to use soil dispersants**—Soils in groups III and IV may have unacceptably high permeability because they contain a preponderance of calcium or magnesium on the clay particles. Unfortunately, field or lab tests to determine when soils are likely to have this problem are not available. The best indication is when parent materials have excessive calcium. Many soils developed from weathering of limestone may have this problem. See the section, Design and construction of clay liners treated with soil dispersants, for more detail. Some states require the routine use of soil dispersants in areas that are known to have high calcium clay soils.

Use concrete or synthetic materials such as geosynthetic clay liners (GCLs) 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 GCLs 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. The most common defects in these liners arise from problems during construction. Forming seams in the field for geomembranes can require special expertise. GCLs have the advantage of not requiring field seaming, but the overlap required to provide a seal at seams is an extra expense. Geomembranes must contain ultraviolet inhibitors if they will be exposed. Designs should include provision for their protection from damage during cleaning operations. Figure 10D–2 shows an agricultural waste storage facility with a geomembrane liner.

Figure 10D–2 Agricultural waste storage facility lined with a geomembrane

When a liner should be considered

A designer should consider seepage reduction beyond that provided by the natural soil at the excavation boundary if any of the conditions listed below are present at a planned site.

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 specified distance from such features. Even if the pond bottom and sides are underlain by 2 feet of naturally low permeability soil, if the depth of liquid in the pond is high enough, computed seepage losses may be greater than considered acceptable. The highest level of investigation and design is required on sites like those described. This will ensure that seepage will not degrade aquifers at shallow depth or aquifers that are of vital importance as domestic water sources.

Excavation boundary of a site is underlain by less than 2 feet of suitably low permeability soil, or an equivalent thickness of soil with commensurate permeability, 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 order of magnitude, the final resultant seepage losses are still likely to be excessive, and a liner should be used if the boundaries of the excavated pond are in this soil group.

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 and computations of specific discharge (unit seepage quantities) is advised. Higher than normal permeability can occur when soils in group III or IV are flocculated or have a blocky structure, which has been discussed previously. These are special cases, and most soils in groups III and IV will not need a liner provided the natural formation is thick enough to result in acceptable predicted seepage quantities.

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 occurs over fractured or fissured rock. If the site is underlain by many feet of intermediate permeability soil, that site could have equivalent seepage losses as one underlain by only 2 feet of low permeability soil.

Specific discharge

(a) Introduction

A rational method of comparing design alternatives at a given site is needed. Such a method allows a designer to determine quantitatively whether conditions at a site are likely to result in acceptable seepage levels. Perhaps more importantly, such a method allows designers to evaluate the effect of changing one or more of the design elements in a site on the predicted seepage quantities.

A somewhat unsatisfactory method of regulating designs to achieve seepage at acceptable levels has been used by some regulatory agencies. The method used in the past by some regulators is to state a minimum thickness of given permeability rate soil type beneath the boundaries of the excavated pond. An example of such a requirement is that the excavated pond must be underlain by at least 2 feet of soils that have a demonstrated permeability of 1×10^{-7} centimeters per second or less.

Using only permeability and thickness of a boundary horizon as a criterion ignores the influence of the depth of liquid on the predicted quantity of seepage from an impoundment. This approach would result in the same design for a clay liner at a site with 30 feet of water as one with 8 feet of water, for instance. A more rational method for stating a limiting design requirement is to compute seepage using Darcy's law as covered in the following section for a unit area of the pond bottom. Total seepage computations consider the seepage from the bottom and from the side slopes of the pond. Seepage from the side slopes can be estimated using an average depth of liquid on the side slopes.

This document presents methods for computing a term called specific discharge to use in comparing alternatives and to document a given design goal for a site. The value of specific discharge is a unit seepage value that does not express the total seepage from a site, but rather provides a value of seepage per square unit area of pond bottom.

Site specific total seepage computations are best made using computer programs that consider the total geometry of the site rather than the simplified unit seepage computations covered below. It is outside the scope of this document to discuss these types of analyses. Specialists who are experienced in using the complex software used for these computations should be consulted for more detailed computations.

The parameters that affect the seepage from a pond with a natural or constructed clay liner are:

- *The size of the pond*—The total bottom area and area of the exposed sides of the pond holding the stored waste solids and liquids.
- *The thickness of low permeability soil at the excavation limits of the pond*—For design, the thickness of the soil at the bottom of the pond is often used because that is where seepage is likely to be highest. In some cases, however, seepage from the sides of the pond may also be an important factor. Seepage from the sides of ponds is best analyzed using finite element flow net programs. In some cases, rather than a single horizon, multiple horizons may be present. As covered in the following examples, one may convert the permeability of a layered system into an equivalent permeability of a single layer to simplify computations.
- The coefficient of permeability of the soil forming the bottom and sides of the pond. In layered systems, an average or weighted permeability may be determined as shown in figure 10D–3.
- The depth of liquid in the pond. The hydraulic gradient as described in following sections is expressed by the following equation. Figure 10D–4 is a definition sketch showing these parameters.

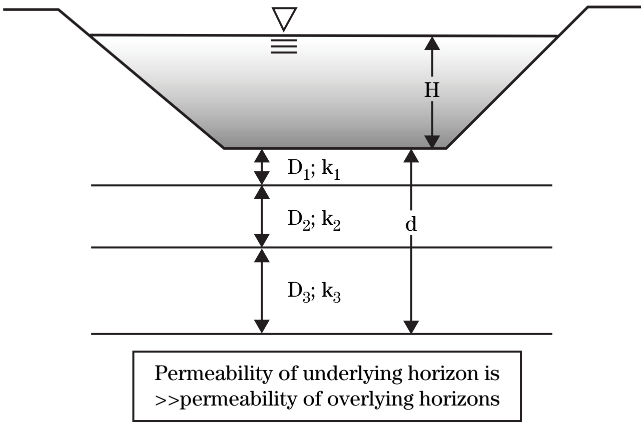
$$i = \frac{\Delta h}{\Delta l} = \frac{H + d}{d}$$

To illustrate the use of this equation, consider example 10D–1:

Example 10D–1

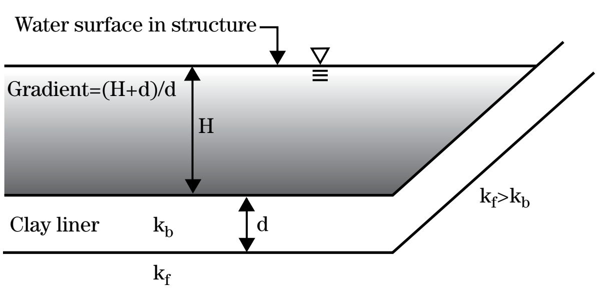
The excavated pond is underlain by 15 feet of soil consisting of three different horizons (fig. 10D–5). The thickness and permeability of each horizon is shown in the sketch. Compute the average vertical permeability of the 15 feet of soil.

Figure 10D–3 Conversion of permeability in layered profile to single value



$$k_{average} = \frac{d}{\frac{D_1}{k_1} + \frac{D_2}{k_2} + \frac{D_3}{k_3}}$$

Figure 10D–4 Definition of terms for clay liner and seepage calculations



(b) Definition of specific discharge

The term specific discharge has been coined to denote the unit seepage that will occur through the bottom of a pond with a finite layer of impervious soil. Specific discharge is the seepage rate for a unit cross-sectional area of a pond. It is derived from Darcy's law as follows. First, consider Darcy's law,

$$Q = k \times i \times A$$

The hydraulic gradient is the term i in the equation, and it is defined in figure 10D–5 as equal to (H+d)/d.

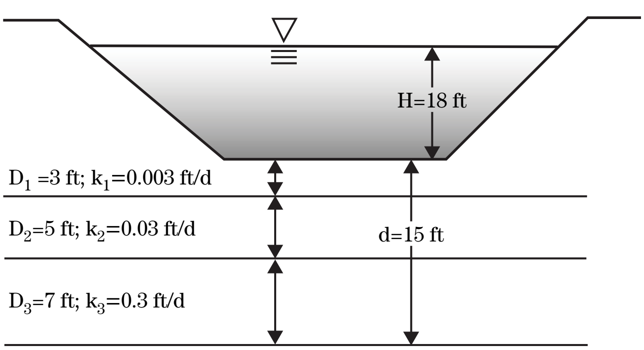
Given: The Darcy's law for this situation becomes:

$$Q = k \times \frac{H + d}{d} \times A$$

where:

Q	=	total seepage through area A	(L^3/T)
k	=	coefficient of permeability (hydraulic conductivity)	($L^3/L^2/T$)
i	=	hydraulic gradient	(L/L)
H	=	vertical distance measured between the top of the liner and required volume of the waste impoundment (fig. 10D–4)	(L)
d	=	thickness of the soil liner (fig. 10D–1)	(L)
A	=	cross-sectional area of flow	(L^2)
L	=	length	
T	=	time	

Figure 10D–5 Idealized soil profile for example 10D–1



Solution

$$k_{average} = \frac{d}{\frac{D_1}{k_1} + \frac{D_2}{k_2} + \frac{D_3}{k_3}}$$

$$k_{average} = \frac{15}{\frac{3}{0.003} + \frac{5}{0.03} + \frac{7}{0.3}} = 0.0126 \text{ ft/d}$$

Rearrange terms:

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

By definition, unit seepage or specific discharge, is Q÷A. The symbol ν is used for specific discharge:

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

The units for specific discharge may be confused with units for permeability because the units are the same. In the metric system, specific discharge and permeability are often expressed in units of centimeters per second. The actual units are cubic centimeters of flow per square centimeter of cross section per second, but this reduces to centimeters per second. Specific discharge is different than permeability because specific discharge is an actual flow rate of liquid through a cross section of a soil mass, whereas permeability is a property of the soil mass itself. Permeability is independent of the gradient in a particular site, whereas specific discharge accounts for both permeability of the soil and the gradient causing the flow, as illustrated. Because gradient is dimensionless, the units of specific discharge and permeability are then the same.

Seepage velocity also has the same units as specific discharge and permeability. In the metric system, seepage velocity would be expressed as centimeters per second. Seepage velocity is computed from given values of specific discharge and porosity as shown in a following section.

To avoid confusion when describing specific discharge and permeability, a strong recommendation is to use different units for specific discharge than for the coefficient of permeability. Common units for permeability are recommended to be in feet per day or centimeters per second. Units for specific discharge should be in gallons per acre per day, acre-feet per acre per day, or acre-inches per acre per day.

To illustrate a typical computation for specific discharge, assume the following:

- A site has a liquid depth of 12 feet.
- The site is underlain by 2 feet of soil that has a coefficient of permeability of 1×10^{-6} centimeters per second (assume that a sample was obtained at the grade of the pond and sent to a laboratory where a flexible wall permeability test was performed on it).
- Compute the specific discharge, ν. First, the coefficient of permeability may be converted to units of feet per day by multiplying the given units of centimeters per second by 2,834.6. Then, k = (1×10^{-6} cm/s)×2,834.6 = 0.002835 foot per day. Then, the specific discharge ν is computed as follows:

$$\begin{aligned}\nu &= k\times\frac{H+d}{d}\\ &= 0.002835\times\frac{12+2}{2}\\ &\cong 0.02\ ft^3/ft^2/d\\ &\cong 0.02\ ft/d\end{aligned}$$

Conversion factors for specific discharge are given in table 10D–5.

To convert the computed specific discharge in the example into units of gallons per acre per day and cubic inches per square inch per day (in/d), use conversion factors given in table 10D–5.

- 0.02 foot per day×325,829 ≅ 6,500 gallons per acre per day
- 0.02×12 = 0.24 cubic inch per square inch per day (in/d)

Table 10D–5 Conversion factors for specific discharge

To convert from	To units of	Multiply by
$ft^3/ft^2/d$	$in^3/in^2/d$	12
$ft^3/ft^2/d$	gal/acre/d	325,829
$in^3/in^2/d$	gal/acre/d	27,152.4
$cm^3/cm^2/s$	gal/acre/d	9.24×10^8
$cm^3/cm^2/s$	$in^3/in^2/d$	34,015

A variety of guidelines have been used and regulatory requirements stated for specific discharge. Usually, requirements or guidelines are that the specific discharge for a given waste storage structure can be no higher than a stated value. An instructive example is to determine the unit seepage that will result from a typical size animal waste storage lagoon with 2 feet of either very good natural soil or a very well constructed, 2-foot-thick clay liner in the bottom of the lagoon. A practical lower limit for the assumed permeability of a compacted clay or a very good natural liner is a coefficient of permeability equal to 5×10^{-8} centimeters per second. This is based on considerable literature on field and laboratory tests for compacted clay liners used in sanitary landfills.

The specific discharge for this ideal condition, then, is as follows, assuming the following:

- The pond has a liquid depth of 15 feet.
- The site is underlain by 2 feet of soil (either a natural layer or a constructed clay liner) that has a coefficient of permeability of 5×10^{-8} centimeters per second
- Compute the specific discharge, ν, using the above equation. First, the coefficient of permeability may be converted to units of feet per day by multiplying the given units of centimeters per second by 2,834.6. Then, $k=(5\times10^{-8}\text{ cm/s})\times2{,}834.6 = 1.42\times10^{-4}$ ft/day. Then, the specific discharge ν is computed as follows:

$$
\begin{aligned}
\nu &= k\times\frac{H+d}{d} \\
&= 1.42\times10^{-4}\times\frac{15+2}{2} \\
&\cong 0.0012\ \text{ft}^3/\text{ft}^2/\text{d} \\
&\cong 0.0012\ \text{ft/d}
\end{aligned}
$$

Converting this into units of gallons per acre per day:

$$0.0012\ \text{ft/d}\times325{,}829\cong393\ \text{gal/acre/d}$$

Table 10D–6 lists typical specific discharge values used by state regulatory agencies, without referencing a specific location. Requirements are different from state to state, and individual designers may regard minimum requirements as too permissive. Some states permit a designer to assume that the initial computed seepage rate will reduce in the future by an order of magnitude by taking credit for a reduction in permeability resulting from manure sealing. The state or local regulations should be used in design for a specific site.

If one assumes at least one order of magnitude of reduction in permeability will occur, the initial specific discharge can be 10 times greater, and the final value for specific discharge will approach a tenth of the initial rate after sealing.

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, ν, divided by the porosity of the soil, n. Seepage velocity = (ν/n). In compacted liners, the porosity usually ranges from 0.3 to 0.5. The result is that the average linear velocity of seepage flow is two to three times the specific discharge value. The units of seepage velocity are L/T.

Table 10D–6 Typical requirement for specific discharge used by state regulatory agencies

Example specific discharge value	Equivalent value in gallons per acre per day
1/56 $in^3/in^2/d$	485
1/8 $in^3/in^2/d$	3,394
1/4 $in^3/in^2/d$	6,788
$1\times10^{-6}\ cm^3/cm^2/s$	924

(c) Design of compacted clay liners

If a site does not have a sufficient thickness of *in situ* low permeability soil horizons to limit seepage to an acceptably low value, a clay liner may be required. Some state regulations may also require a constructed clay liner regardless of the nature of the *in situ* soils at a site. Regulations sometimes require a specific thickness of a compacted soil with a demonstrable permeability of a given value. An example of this is a state requirement that a waste storage pond must have in the bottom and sides of the pond at least 2 feet of compacted clay with a demonstrated coefficient of permeability of 1×10^{-7} centimeters per second.

Clay liners may also be designed based on a stated allowable specific discharge value. Computations may be performed as detailed in following sections to determine a design that will meet a design specific discharge goal in two basic ways.

- Using the required specific discharge, the given depth of liquid in the pond, and an assumed thickness for the liner, the required coefficient of permeability of the liner can be computed.
- Using the required specific discharge, the given depth of liquid in the pond, and an assumed compacted permeability for the liner, the required thickness of the liner can be computed.

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—Determine (from a geologic investigation) the thickness and permeability of horizons of natural clay underlying the bottom of the planned excavated pond. Investigate to a minimum of 2 feet below the planned grade of the pond or to depths required by state regulations. If natural low permeability horizons at least 2 feet thick do not underlie the site or an equivalent thickness of soil with different permeability does not exist below the planned excavation, assume that a compacted clay liner (with or without amendments) will be constructed. The liner may be constructed of soils from the excavation if they are suitable for use, or they may be imported from a nearby borrow source.

Step 3—Measure or estimate the permeability of the natural horizons or determine a design permeability for the compacted clay liner. Use a value for allowable discharge from state regulations. If no regulations are provided, NRCS has found on a limited basis that sites where liners were in place that resulted in initial seepage rates of less than 5,000 gallons per acre per day, that ground water conditions have not been found to be degraded in the time that observations have been made. One should understand that with the current state of technology, no absolutely safe seepage rate or specific discharge can be stated, only a reasonable value based on current knowledge. Should state regulations be more restrictive or an individual designer feels that more conservative limiting seepage is advisable, that rate should be used in computations.

Step 4—Compute the specific discharge using the values of head in the pond and thickness of natural horizons and their equivalent permeability in the specific discharge equation. Use procedures shown in example 10D–1 for obtaining a weighted permeability for the natural horizons.

Step 5—If the computed specific discharge meets design objectives, the site is satisfactory without additional design and may be designed and constructed.

Step 6—If the computed specific discharge at the site does not meet design objectives, use either method A or method B shown to design a compacted clay liner.

Notes to design steps:

- The calculated thickness of liner required is sensitive to the value of permeability used and the assumed allowable specific discharge value. The best and most economical way to reduce the required liner thickness is 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. As described later in this document, lowering the coefficient of permeability by a factor of 100 is possible with some of these design changes.
- An alternative design approach to determining the required thickness of a given permeability liner to meet a specific discharge goal 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 from the specific discharge equation as shown later in this section.
- The liner soil must be filter-compatible with the natural foundation upon which it is compacted. Filter compatibility is determined by criteria in NEH633, chapter 26. As long as the liner soil will not pipe into the foundation, the magnitude of hydraulic gradient across the liner need not be limited. 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 clay liner is given in CPS 521D. The minimum thickness varies with the depth of liquid in the pond. In no case should a compacted clay liner thinner than 1 foot be constructed.
- Clay liners constructed by mixing bentonite with the natural soils at a site are recommended to have a minimum thickness shown in CPS 521C. 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 bentonite treated liner is needed to meet suggested seepage criteria, the CPS 521C would still be consulted.
- 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. CPSs provide guidance for protection.
- 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 described 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 (or a bentonite treated 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 created by desiccation. A protective insulating blanket of less plastic soil may be effective in protecting underlying more plastic soil from desiccation during these exposure

periods. CPSs address this important consideration. If a clay liner (or a bentonite treated 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 created by desiccation. A protective insulating blanket of less plastic soil may be effective in protecting underlying more plastic soil from desiccation during these exposure periods. CPSs address this important consideration.

- Federal and state 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.

Method A—Using assumed values for the coefficient of permeability of a compacted clay based on laboratory tests of the proposed liner soil, compute the required thickness of a liner to meet the given specific discharge design goal. In the absence of more restrictive state regulations, assume an acceptable specific discharge of 5,000 gallons per acre per day. The required thickness of a compacted liner can be determined by algebraically rearranging the specific discharge equation, as follows: Derivation of the equation is shown later in this section. Terms are defined in figure 10D–4.

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

Note: If the k value assumed 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. Another way of stating this is that 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, in comparable units. Note also that CPS 521D has requirements for minimum thickness of compacted clay liners. If the computed value for the required thickness in the above equation is less than that given in CPS 521D, then the values in the CPS must be used anyway.

Example 10D–2—Computations for method A used to design a clay 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 6.5×10^{-7} centimeters per second (0.00184 ft/day) for soils compacted to 95 percent of maximum Standard Proctor dry density at a water content 2 percent wet of optimum. The state requirement for the site requires a specific discharge no greater than one-eighth of an inch per day. Compute the required thickness of liner to be constructed of the stated permeability that will achieve this specific discharge. What would be the effect of manure sealing on this computed requirement, if assumed reduction of seepage from manure sealing were permitted and was elected for use in the design.

Solution:

Step 1—First, convert the required specific discharge into the same units as will be used for the coefficient of permeability. Using values for permeability of feet per day, convert the stated one-eighth inch per day specific discharge requirement into feet per day. To convert, divide one-eighth by 12 to obtain a specific discharge requirement of 0.010417 ft/day. It is given that the k value at the design density and water content is 0.00184 foot per day. Calculate the required minimum thickness of compacted liner as follows:

The equation for required d is:

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

Using English system units, substituting the given values for H and k, assuming an allowable specific discharge, ν, of 0.010417 foot per day, then

$$d = \frac{0.00184 \times 12}{0.010417 - .00184} = 2.6 \text{ ft}$$

CPS 521D requires a pond with a depth of water of 12 feet to have a minimum thickness liner of 1 foot, so the 2.6 foot requirement governs.

Step 2—Assume that regulations permit considering the benefit of seepage reduction for manure sealing of one order of magnitude. Then, the design specific discharge may be 10 times the stated permissible value because manure sealing will reduce the initial seepage to the stated acceptable limits in a year or so of operation. The allowable specific discharge then becomes 10×(0.010417 ft/day) = 0.10417 ft/day. Substituting into the equation solving for thickness of liner required:

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

$$d = \frac{0.00184 \times 12}{0.10417 - 0.00184} = 0.2 \text{ ft}$$

Conclusion:
In this case, the minimum thickness liner required in CPS 521D of 1 foot would be designed.

Method B—Using a given value for depth of liquid in the pond, assumed values for the thickness of a compacted clay based on construction considerations, CPS 521D requirements, state regulations, or the preference of the designer, compute the required permeability of a liner to meet the given specific discharge design goal. In the absence of more restrictive state regulations, assume an acceptable specific discharge of 5,000 gallons per acre per day. The required permeability of a compacted liner can be determined by algebraically rearranging the specific discharge equation as follows: Derivation of the equation is shown later in this section. Terms are defined in figure 10D–4.

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

If the computed value for the required permeability in the above equation is less than 5×10^{-8} centimeters per second (1.4×10^{-4} ft/day), NRCS engineers' experience is that lower values than this are not practically obtainable and a thicker liner or synthetic liners should be used to achieve design goals.

Example 10D–3—Computations for method B used to design a clay liner

Given:
Site design has resulted in a required depth of waste liquid, H, in the constructed waste impoundment of 19 feet. CPS 521D requires a liner that is at least 18 inches (1.5 feet) thick. The site is in a state that allows NRCS design guidance of 5,000 gallons per acre per day to be used in the design. The NRCS requirement assumes that manure sealing will reduce this seepage value further and no additional credit should be taken.

Solution:

Step 1 First, convert the required specific discharge into the same units as will be used for the coefficient of permeability. Using values for permeability of feet per day, convert the stated 5,000 gallons per acre per day specific discharge requirement into feet per day. To convert, divide 5,000 by 325,829 to obtain a specific discharge requirement of 0.0154 foot per day. The thickness of liner is given to be 1.5 feet. Calculate the required coefficient of permeability of the compacted liner as follows

The equation for required k is:

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

Using English system units, substituting the given values for H of 19 feet and for d of 1.5 feet, assuming an allowable specific discharge, ν, of 0.0154 foot per day, then

$$k = \frac{\nu \times d}{H + d}$$
$$= \frac{0.0154 \times 1.5}{19 + 1.5}$$
$$= 1.1 \times 10^{-3} \text{ ft/d}$$
$$= 4.0 \times 10^{-7} \text{ cm/s}$$

Step 2—The designer should coordinate testing with a laboratory to determine what combinations of degree of compaction and placement water content will result in this value of permeability or less. Design of the 1.5 feet thick liner may proceed with those recommendations.

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 loose 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–6). Figure 10D–7 shows two sites where this method of construction is being used.

This construction method has the advantage over the stair step method that the layers of compacted clay are oriented perpendicular to flow through the liner in this method. In the stair step method, flow is parallel to the orientation of the layers forming the compacted liner on the pond sides. This method also lends itself to constructing thinner lifts. Side slopes should be an absolute minimum of 3H:1V 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 slopes of many compacted liners in ponds constructed using this method use 4H:1V slopes so that equipment will exert more normal pressure on the slope than downslope pressure.

Figure 10D–6 Methods of liner construction (After Boutwell 1990)

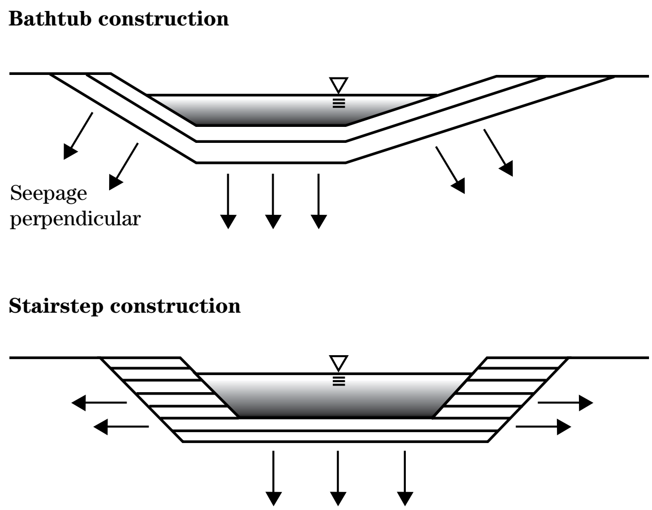


Figure 10D–7 Bathtub construction of clay liner *(photo courtesy of NRCS Virginia)*

(2) Stair step

The stair step method of construction is required if the side slopes of the pond are any steeper than about 3H:1V. A thicker blanket, measured normal to the slope, will result compared to the bathtub method of construction (figs. 10D–6 and 10D–8). This is a positive factor in seepage reduction, but it will probably be more expensive because of the larger volume of soil required. An advantage of this method is that it allows steeper side slopes and thus the surface area of the pond exposed to rainwater accumulation is smaller than a bathtub construction would permit. 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. Another disadvantage of this method is that a larger volume of excavation is required to accommodate the thicker blanket.

First, the pond is excavated with extra excavation for the compacted liner (fig. 10D–8(a)). Borrow soil is imported with a truck or scraper and spread in thin lifts prior to compaction. This photo shows the first layer being constructed on the sides of the pond. This pond used a bentonite application. Each lift of soil is compacted with a sheepsfoot roller to obtain the desired dry density at the specified water content (fig. 10D–8(b)). The interior liner is constructed by bringing up lifts the full depth of the pond. Photo 10D–8(c) provides an overview of the stair-step process of constructing a clay liner in an animal waste storage pond. After the sides are constructed, some of the liner is shaved off and used to construct a liner in the bottom of the pond.

(c) Soil type

Soils in groups III and IV are the most desirable for constructing a clay liner (table 10D–2). Some soils in group II may also be good materials for a clay liner but definitely require laboratory testing to document their permeability characteristics. Soils in group I always require bentonite to form a liner with acceptably low permeability. Some soils in group II may also require bentonite to be an acceptable material for a liner. Some soils in groups III and IV require a soil dispersant to create an acceptably low permeability.

(1) Classification

The most ideal soils for compacted liners are those in group III. The soils have adequate plasticity to provide a low permeability, but the permeability is not excessively high to cause poor workability. Group IV soils can be useful for a clay liner but their higher plasticity index ((PI) greater than 30) means they are more susceptible to desiccation. If clay liners are exposed to hot dry periods before the pond can be filled, desiccation and cracking of the liner can create an objectionable increase in permeability. A protective cap of lower PI soils is often specified for protection of higher PI clay liners to prevent this problem from developing. Figure 10D–9 illustrates the structure that can occur with plastic clays where clods are present.

Highly plastic clays like those in Group IV 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–9.

(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. Soil containing hard clayey clods is difficult to break down and moisten thoroughly. Adding water to the soil is difficult because water penetrates the clods slowly. High speed rotary pulverizers are sometimes needed if conditions are especially unfavorable. If soils containing large clay clods are not treated properly, the resultant permeability will be much higher than might otherwise be true. Figure 10D–9 shows the structure that results from compacting soils containing clods that are not adequately broken down.

Figure 10D–8 Stair step method *(photo credit John Zaginaylo, PA, NRCS*

(a)

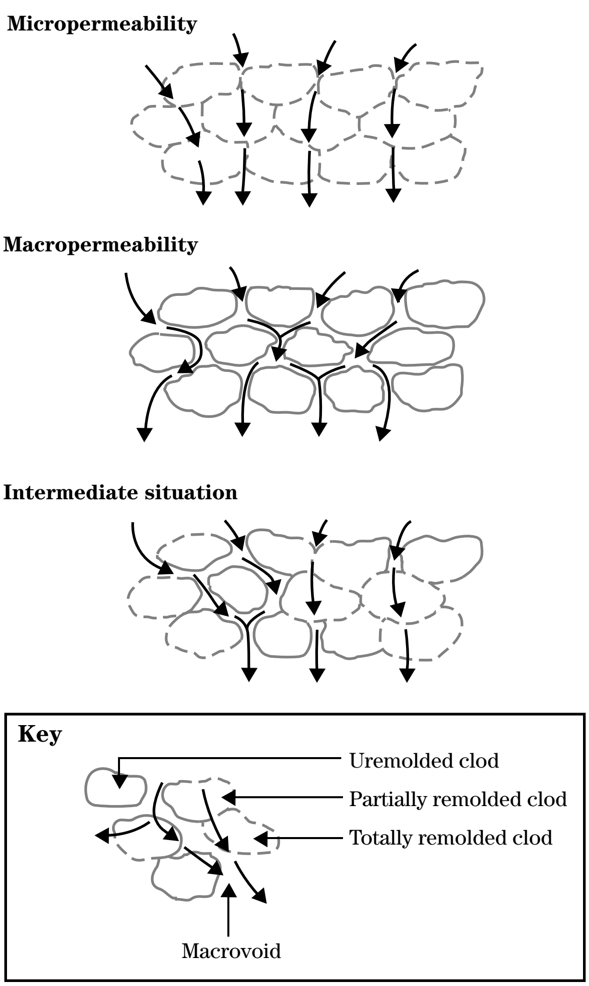
(b)

(c)

(d) Natural water content of borrow

The water content of soils used to construct a clay liner is the most important factor in obtaining a low permeability liner. If soils are too dry, they cannot effectively be compacted to a condition where their structure is acceptable and their permeability will be higher than desirable. Compacting a soil at the proper water content assures a structure that is most favorable to a low permeability. Adding water to compacted clay liners is an additional expense that must be considered. A good rule of thumb is that it requires about 3.2 gallons of water to increase the water content of a cubic foot of compacted soil by 1 percent. Adding more than 2 or 3 percent water to compacted soil is difficult on the fill and should be done in the borrow area prior to construction.

Figure 10D–9 Macrostructure in highly plastic clays with poor construction techniques (from Hermann 1987)



(1) Dry conditions in the borrow

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 when processing is solely 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 the soils in the borrow are too wet for effectively compacting them.

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 Compute the highest dry density to which the soil can be compacted at this water content using the following equation. The value for G_s can often be assumed to be about 2.68, but if local experience shows this value is not representative, adjusted values should be used. Some volcanic derived soils have G_s values as low as 2.3 and some other soils with unusual mineral content may have values of G_s as high as 3.0, but 2.68 is a commonly used assumption.

$$\text{Achievable } \gamma_{dry} \text{ lb/ft}^3 = \frac{62.4}{\frac{w_n\%}{90} + \frac{1}{G_s}}$$

Step 3 Perform a Standard Proctor (ASTM D698) compaction test on the same soil and determine the maximum dry density value. Compute the achievable degree of compaction by dividing the computed value of achievable dry density by the maximum Standard Proctor dry density.

Step 4 If the computed achievable degree of compaction is less than 95 percent, then drying of the sample will probably be required to obtain the required low permeability. In rare cases, compaction to a lower degree, such as 90 percent of Standard Proctor, at higher water contents will achieve an acceptably low permeability. Laboratory tests should be performed to ensure the permeability achievable at these low degrees of compaction.

Note: The experience of NRCS engineers is that when the natural water content of a soil is more than 4 percent above optimum water content, it is not possible to achieve 95 percent compaction. Computations should always be performed as this rule of thumb sometimes has exceptions. In most cases drying clay soils simply by disking is somewhat ineffective and it is difficult to reduce their water content by more than 2 or 3 percent with normal effort. It is often 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.

Another way of examining this problem is to assume that soils must be compacted to 95 percent of their Standard Proctor (ASTM D698) dry density and then compute the highest water content at which this density is achievable. Commonly, soils are difficult to compact to a point where they are more than 90 percent saturated. The following equation is used to determine the highest feasible placement water content at which the dry density goal is achievable:

$$\text{Highest placement w(\%)} = \frac{90(\%)}{100} \times \left[\frac{62.4}{\gamma_{dry}\ \text{lb/ft}^3} - \frac{1}{G_s} \right]$$

Example 10D–4—Compute the achievable dry density of a potential borrow source.

Given:
A borrow source is located and found to be in a desirable group III type. The soil has 65 percent finer than the No. 200 sieve and a PI of 18. The soil was sampled and placed in a water tight container and shipped to a soils laboratory. The natural water content of the soil is measured to be 21.8 percent. The lab also performed a specific gravity (G_S) test on the soil, and measured a value of 2.72. A Standard Proctor Test was performed on the sample and values for maximum dry density of 108.5 pounds per cubic foot and an optimum water content of 17.0 percent is measured.

Find:
The maximum degree of compaction of this soil at the measured water content. If the soil is too wet to be compacted to 95 percent of maximum standard Proctor dry density, how much will it have to be dried to achieve compaction to 95 percent of maximum density?

$$\text{Achievable } \gamma_{dry}\ \text{lb/ft}^3 = \frac{62.4}{\frac{w_n\%}{90} + \frac{1}{G_s}}$$

$$\text{Achievable } \gamma_{dry}\ \text{lb/ft}^3 = \frac{62.4}{\frac{21.8\%}{90} + \frac{1}{2.72}} = 102.3\ \text{lb/ft}^3$$

Next, compute the achievable degree of compaction by dividing the achievable dry density by the maximum Standard Proctor dry density, expressed as a percentage. The achievable degree of compaction is then equal to 102.3 divided by 108.5×100 = 94.3 percent.

Now, determine what the wettest that the sample could be and achieve 95 percent compaction. Ninety-five percent of the maximum Standard Proctor dry density is 0.95×108.5 = 103.1 pounds per cubic foot. Substitute this value into the equation given:

$$\text{Highest placement w\%} = \frac{90}{100} \times \left[\frac{62.4}{\gamma_{dry}\ \text{lb/ft}^3} - \frac{1}{G_S} \right]$$

$$\text{Highest placement w\%} = \frac{90}{100} \times \left[\frac{62.4}{103.1\ \text{lb/ft}^3} - \frac{1}{2.72} \right] = 21.4\%$$

This computation conforms very well to the rule of thumb given that it is difficult to achieve 95 percent degree of compaction if the natural water content is greater than 4 percent above optimum. The stated value for optimum water content is 17.0 percent, so the rule of thumb says that if the natural water content exceeds 21.0 percent, achieving 95 percent degree of compaction will be difficult.

(e) Method of excavation and methods of processing

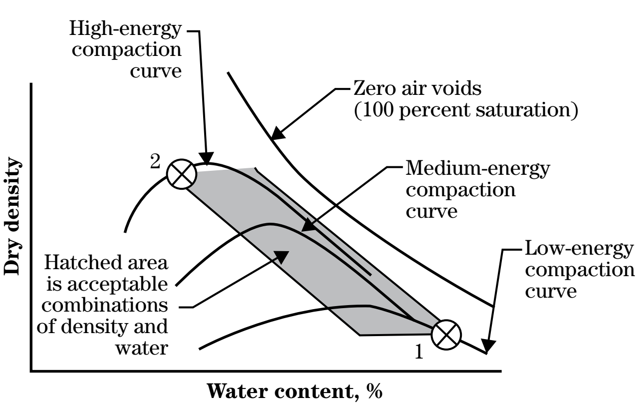
(1) Clods in borrow soil

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.

Figure 10D–10 Construction of clay liner for an animal waste pond



(f) Macrostructure in plastic clay soils

Clods can create a macrostructure in a soil that results in higher than expected permeability because of preferential flow along the interfaces between clods. Figure 10D–9 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 for most earth fill projects 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 is usually based on engineering property tests such as shear strength, bearing capacity, and permeability. When permeability is the primary engineering property of interest, as would be the case for a compacted clay liner, an alternative type of compaction specification should be considered. The reason for this is a given permeability value can be attained for many combinations of compacted density and water contents (Daniels 1990). Figure 10D–10 illustrates a window of compacted dry density and water content in which a given permeability could be obtained for an example soil.

Example 10D–5

Given: Assume that a given soil is being used to construct a clay liner for an animal waste storage pond. Assume that it is a desirable moderately plastic silty clay that would classify as CL in the USCS. In case 1, the soil being obtained from a nearby borrow area is somewhat high in its natural water content. The contractor elects to use lighter construction equipment that applies a relatively low energy in compacting the soil. The result is the soil is compacted to a condition where the compacted density is relatively low and the placement water content is relatively high. This is labeled as point 1 in the figure 10D–10. In case 2, the same soil is being used, but the site is being constructed in a drier time of year. The contractor elects to use a larger sheepsfoot roller and apply more passes of the equipment to achieve the desired product. The result is that the same soil is compacted to a significantly higher density at a significantly lower water content. This is labeled point 2 in the figure 10D–10. Laboratory tests can be used to establish the bounding conditions and arrive at a window of acceptable densities and water contents for a clay liner. Figure 10D–11 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.

Mitchell (1965) was instrumental in explaining how the permeability of clay soils is affected by the conditions under which they were compacted. Figure 10D–12 summarizes results of one series of experiments summarized in the study. Two samples of a soil were compacted using different energy at different water contents and their permeability was measured. Soil C was compacted using a high energy, like that used when a heavy sheepsfoot roller passed over each compacted lift multiple times. Soil B was compacted using a lower energy, equating to a smaller roller with a smaller number of passes used in the compaction process.

Figure 10D–12 shows some of the data from Mitchell's study. Curve C in the figure is for a soil compacted with high energy, like a heavy tamping roller compacting the soil numerous times. Curve B is for a soil compacted with lower energy, like a smaller roller operated at less passes. The curves show the relationship between the permeability of the compacted soil and the compaction water content, for the two energies used. The following general principles are seen:

- The permeability of the low energy soil (curve B) is high unless the compaction water content is significantly wet of optimum. Very high permeability results for compaction dry of optimum.
- The permeability of the higher energy soil (curve C) is lower for all water contents than the curve B energy tests.
- For high energy (curve D), relatively low water contents are achievable at from slightly dry of optimum and wetter. Very low permeability values are obtained for the higher energy compaction when the molding water content is wet of optimum.

Figure 10D–11 Effect of water content and compactive effort on remolding of soil structure in clays (from Lambe 1958)

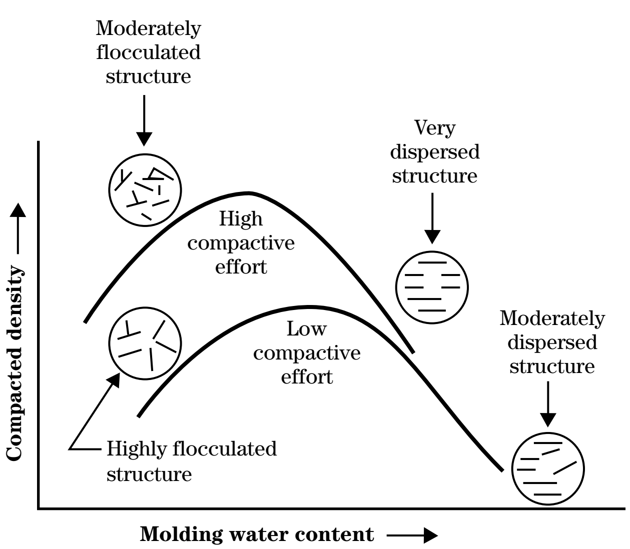
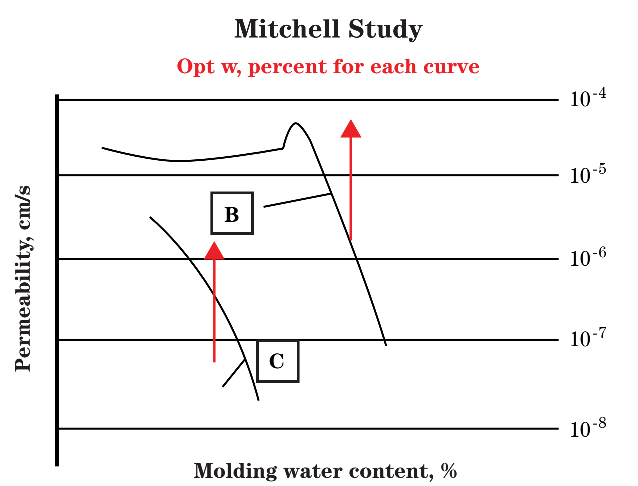


Figure 10D–12 Plot showing effect of molding water content on permeability



(2) Percent saturation importance

Benson and Boutwell (2003) studied the correlation between field measured permeability values on compacted liners with laboratory measured values. They found that when soils were compacted at drier water contents, even if a high density were obtained, that correlation between field and lab permeability test values was poor. They found good correlation when soils were compacted at relatively higher water contents. Clods in clay soils are probably not broken down as well at lower compaction water contents which explains the higher permeability in the field. In lab tests, breaking down clods and obtaining test specimens without a structure is easier.

The conclusions of Benson and Boutwell's research was that if a designer is going to rely on laboratory permeability tests to predict the permeability of a compacted clay liner, the following rules of thumb must be followed:

- Soils must be compacted wet of the line of optimums. Specifications should require that at least 80 percent of field density tests performed during construction of a clay liner should show soils are at water contents wetter than the line of optimums for the soil being used.
- Soils should be compacted from 2 to 4 percent wetter than the line of optimums for the soil being used. On average, most soils have an optimum water content that is about 85 percent of saturated water content.

(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, thickness of the lift, and 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 significantly wet at optimum water content, 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 counter-productive 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.

(j) Freeze-thaw and desiccation

(1) Freeze-thaw

Compacted clay liners may become damaged when the liner is exposed during freezing weather. Articles by Kim and Daniel (1992) and Benson and Othman (1993) describe the effects of freezing on clay liners and how the damage resulting from freezing may be permanent. Laboratory tests show that permeability rates may increase by 2 to 3 orders of magnitude (100–1,000 times).

(2) Desiccation

Compacted clay liners may also be damaged when the liner is exposed during hot, dry weather after construction and before the pond is filled. Desiccation may also occur during periods the pond is emptied. Articles by Daniel and Wu (1993) and Kleppe and Olson (1985) describe factors that affect desiccation. Using the sandiest soil available that will be adequately impermeable is helpful and compacting the soil as dense and dry as practical while still achieving the design permeability goal is also helpful. Protective layers must be at least 12 inches thick to be effective, and even thicker layers may be needed for more plastic clay liners.

Design and construction of bentonite amended 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. Constructing a bentonite amended liner is covered in CPS 521C.

(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 United 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 if its level of activity is 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 the level of activity based on a test of its free swell. Bentonite should have a minimum free swell of at least 22 millimeters in 24 hours. There is not an ASTM standard test method for determining free swell. A procedure that can be used to determine free swell is as follows:

- Prepare a sample for testing that consists of material from the total sample that is smaller than a #30 sieve and larger than a #50 sieve.
- Fill a 100 milliliter graduated cylinder with 100 milliliters of distilled water.
- 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.
- 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 24 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 24 hours.

Figure 10D–13 shows an excellent quality bentonite reaction to the test.

Figure 10D–13 A simple test consists of placing 2 grams of granular bentonite carefully in a calibrated beaker.

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 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 CPS 521C, Pond Sealing or Lining, Bentonite Sealant, provide minimum required total liner thicknesses for various depth of liquids in the finished pond. Required thicknesses are from 6 inches for ponds with less than 8 feet depth of liquid to 2 feet for ponds with more than 24 feet depth of liquid.

CPS 521C provides guidance on approximate rates of application of bentonite based on testing performed by the NRCS laboratories. Rates provided in the CPS are in terms of pounds of bentonite required for each 1-inch thickness of liner. The total amount of bentonite is then equal to the thickness of the liner times the rate per inch. For instance, for relatively clean sands being treated with bentonite, those soils that classify as SP or SW in the USCS, the CPS 521C suggests a rate of application of 0.625 pounds of bentonite per inch of constructed liner. If a pond had a water depth of between 8 and 16 feet, the CPS 521C requires a minimum 12-inch thick treated liner. The total amount of required bentonite would then be $0.625 \times 12 = 7.5$ pounds per square foot of liner. The rates of application provided in CPS 521C assume that high quality sodium bentonite from Wyoming/South Dakota/Montana with a free swell of at least 22 milliliters is being used. The rates also assume that finely ground bentonite is being used. If coarsely ground bentonite or bentonite that is not expected to meet the free swell criterion of 22 milliliters is planned to be used, the rate of application should be based on laboratory tests and not on the tables in CPS 521C.

The recommended procedure to arrive at a design for a bentonite treated liner then is as follows:

Step 1 Obtain a sample of the soil to which the bentonite is to be added. Have the sample tested in a soils laboratory to determine its basic index properties, including percent fines and plasticity.

Step 2 Have a standard Proctor (ASTM D698) test performed to determine the maximum dry density and optimum water content.

Step 3 From the preliminary design of the site, determine the final depth of water in the structure. Use CPS 521C to determine the minimum thickness of liner required.

Step 4 Using given or assumed values for allowable specific discharge, compute the required permeability of the bentonite treated liner.

Step 5 Coordinate with a soils laboratory on testing to determine what degree of compaction, water content, and rate of application of the proposed additive is required to obtain this permeability. Consider whether high quality (free swell > 22 mL) is being used and whether finely ground or coarsely ground bentonite is proposed.

Step 6 Design the final liner based on the procedure.

Example 10D–5—To illustrate this process for a bentonite treated liner, a comprehensive example is provided.

Given:
A waste storage pond is planned with a depth of liquid of 21 feet. The state requirement for the location is a specific discharge no greater than one-fifty-sixth of an inch per day of seepage. Assume the soils at grade have been tested and found to be suitable for bentonite treatment. Find the minimum thickness liner required according to CPS 521C and determine the required permeability to meet this specific discharge requirement.

First, consult CPS 521C to determine the minimum required thickness. From the table in the CPS, a liner should be a minimum of 18 inches thick (1.5 feet).

Convert the specified unit seepage rate (specific discharge) of one-fifty-sixth of an inch per day into the same units as will be used for permeability (centimeters per second). To convert, multiply:

$$\frac{1}{56} \times 2.94 \times 10^{-5} = 5.25 \times 10^{-7}$$

The thickness of the liner and depth of liquid in the pond must also be converted. To convert the liner thickness of 18 inches to centimeters, multiply by 2.54, which equals a liner thickness, d, of 45.72 centimeters. The liquid depth of 21 feet is equal to

$$21 \times 12 \times 2.54 = 640.1 \text{ cm}$$

Using the equation discussed previously, solve for the required permeability:

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

$$k = \frac{5.25 \times 10^{-7} \times 45.72}{640.1 + 45.72} = 3.5 \times 10^{-8}$$

The designer should coordinate with a soils laboratory to determine how much bentonite of given quality is required to obtain this low a permeability. In the experience of NRCS engineers, relying on this low a permeability means that construction quality control must be excellent and all the procedures and materials used are of highest quality. Seldom should designs for clay liners rely on a design permeability much lower than 5×10^{-8} centimeters per second. A designer might want to proceed with this design but require a slightly thicker liner (24 in.) to provide additional assurance of obtaining the design specific discharge.

CPS 521C recommends considering the addition of a protective soil cover over the bentonite treated compacted liner in waste impoundments. There are several reasons why a soil cover should be provided:

- Desiccation cracking of the liner after construction and prior to filling is a significant problem because the bentonite used in treatment is highly plastic.
- 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.

- Bentonite treated liners are generally less thick than compacted clay liners. The thinner bentonite treated liner that is exposed during periods when the impoundment has been drawn down can more easily erode unless it is protected. Rilling due to rainfall on the exposed slopes can seriously impair the water tightness of the liner.
- Over excavation by mechanical equipment during sludge removal can damage the liner. A minimum thickness of 12 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 smooth wheeled steel rollers, as shown in figure 10D–14. Crawler tractor treads are also effective. Sheepsfoot rollers that are often used in constructing clay liners are not as effective. CPS 521C 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 pulvermixer is the best method of obtaining the desired mix (fig. 10D–15). 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.

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

Bentonite treated liners are often constructed in 4-inch compacted lift thicknesses. Liners should be designed in multiples of 4 inches for this reason. Often, the first layer of bentonite treated soil is the soil exposed in the bottom of the exaction. By applying bentonite to the exposed grade, disking it in to a depth of about 6 inches, and compacting it, the first layer is formed. Subsequent lifts are formed by importing loose fill adequate to form additional 4-inch-thick lifts.

Figure 10D–14 Smooth wheeled steel roller compactor

Figure 10D–15 Pulvermixer

Design and construction of clay liners treated with soil dispersants

The Permeability of Soils section of this appendix 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) and polyphosphates. The two most common polyphosphates are tetrasodium pyrophosphate (TSPP), and sodium tripolyphosphate (STPP). Common salt (NaC_1) has been used in the past, 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 other two dispersants. However, because soda ash may be considerably less expensive, it may be the most economical choice in many applications.

(b) Design details for dispersant treated clay liner

CPS 521B, Pond Sealing or Lining, Soil Dispersant, provides minimum thicknesses of liners created by using the dispersant treated layer method, based on the depth of liquid in the pond. CPS 521B provides guidance on approximate rates of application of soil dispersants based on testing performed by the NRCS laboratories. Rates provided in the CPS are in terms of pounds of dispersant required for each 6-inch layer of liner. The total amount of dispersant is then equal to the number of 6 inch lifts in the completed liner times the rate per lift.

Example 10D–6

Assuming for the purposes of this illustration that soda ash is planned for use at a site, CPS 521B suggests a rate of application of 15 pounds of soda ash square foot per one hundred pounds for each 6 inches of constructed liner. Assuming for the purposes of this illustration that the site has a water depth of between 8 and 16 feet, the CPS 521C requires a minimum 12-inch thick treated liner. The total amount of required soda ash then would then be 15 pounds per 100 square foot times two 6-inch lifts equals 30 pounds of soda ash per 100 square foot of liner. The rates of application provided in CPS 521C assume average soils and are based on historical testing in NRCS laboratories. Laboratory testing may show that smaller amounts of dispersant can be used and achieve the required permeability.

The recommended procedure to arrive at a design for a soil dispersant treated liner then is:

Step 1 Obtain a sample of the soil to which the dispersant is to be added. Have the sample tested in a soils laboratory to determine its basic index properties, including percent fines and plasticity.

Step 2 Have a standard Proctor (ASTM D698) test performed to determine the maximum dry density and optimum water content.

Step 3 From the preliminary design of the site, determine the final depth of water in the structure. Use CPS 521B to determine the minimum thickness of liner required.

Step 4 Using given or assumed values for allowable specific discharge, compute the required permeability of the dispersant treated liner.

Step 5 Coordinate with a soils laboratory on testing to determine what degree of compaction, water content, and rate of application of the proposed additive is required to obtain this permeability. Consider local practice and consult suppliers to determine the relative costs of soda ash versus polyphosphates.

Step 6 Design the final liner based on the procedure.

Example 10D–7—To illustrate this process for a dispersant treated liner, a comprehensive example is provided.

Given:
A waste storage pond is planned with a depth of liquid of 18 feet. The state requirement for the location is a specific discharge no greater than 2,000 gallons per acre per day of seepage. Assume the soils at grade have been tested and found to require dispersant treatment. Find the minimum thickness liner required according to CPS 521C and then determine the required permeability to meet this specific discharge requirement.

Solution:
First, consult CPS 521B to determine the minimum required thickness. From the table in the CPS, a liner should be a minimum of 12 inches thick (1.0 feet).

Convert the specified unit seepage rate (specific discharge) of 2,000 gallons per acre per day into the same units as will be used for permeability (cm/s). To convert, divide the seepage rate in gallons per acre per day by 9.24×10^{8}. Divide 2,000 by 9.24×10^{8} to get a specific discharge of 2.2×10^{-6}. The thickness of the liner and depth of liquid in the pond must also be converted. To convert the liner thickness of 12 inches to centimeters, multiply by 2.54, which equals a liner thickness, d, of 30.48 centimeters. The liquid depth of 18 feet is equal to

$$18\times12\times2.54 = 548.64 \text{ cm}$$

Using the equation described previously, solve for the required permeability:

$$\begin{aligned} k &= \frac{\nu\times d}{H+d} \\ &= \frac{2.2\times10^{-6}\times30.48}{548.64+30.48} \\ &= 1.1\times10^{-7} \text{ cm/s} \end{aligned}$$

The designer should coordinate with a soils laboratory to determine how much soil dispersant of the desired type is required to obtain this low a permeability. In the experience of NRCS engineers, obtaining this value of permeability using a soil dispersant should not require special effort or unusual amounts of additive. At the same time, seldom should designs for dispersant treated clay liners rely on a design permeability much lower than 5×10^{-8} centimeters per second. A designer should proceed with this design specifying the application rate recommended by the soils lab and a 1-foot-thick liner to obtain the design specific discharge.

(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. CPS 521B 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 to mix soil dispersant thoroughly with floculLated clay soil is the best method of obtaining the desired mix (fig. 10D–16). 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 3H:1V. On the other hand, compacting along rather than up and down the slopes could be difficult on slopes as steep as 3H:1V. For some sites, slopes as flat as 3.5H:1V or 4H:1V should be considered for this factor alone.

Figure 10D–16 Rototiller

Designs usually 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.

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 (fig. 10D–17). This problem is most likely to occur during the period before the waste impoundment is filled and during periods when the impoundment may be

Figure 10D–17 Failure of compacted liner from uplift forces below clay blanket

emptied for maintenance and cleaning. Figure 10D–18 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 factor of safety 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 factor of safety 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. Often, sites where seasonal high water tables are anticipated include a design for a perimeter drain to collect the water and prevent this type of damage. Other options include building concrete structures above ground.

Another situation where a clay liner may be damaged from hydrostatic pressure under the blanket can occur when a site is located in a flood plain of a stream or river. The site may have to be built above ground level in this type of location to avoid a seasonal high water table. Figure 10D–19 illustrates the problem that may occur that must be considered by designers. A temporary flood condition in the flood plain can subject the agricultural waste storage pond to a differential head when the pond is empty. The pond could be empty shortly following construction or it could be empty to apply waste to crops. Uplift pressure may cause piping of sandy horizons underlying the site, sand boils, and soughing of side slopes can occur as shown in figure 10D–19. The photo shows a clay-lined animal waste storage structure where the clay liner was damaged from excessive hydrostatic uplift forces caused to temporary storage of flood waters outside the embankment.

Figure 10D–18 Uplift calculations for high water table (from Oakley 1987)

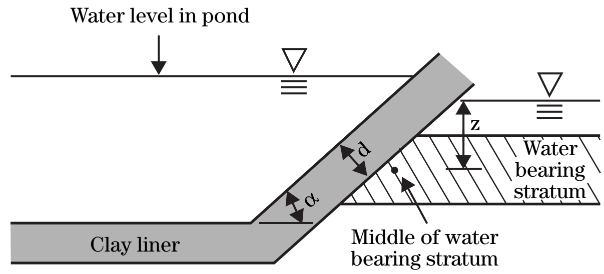


Figure 10D–19 Uplift conditions caused by temporary flood stage outside lagoon

(a) Soil mechanics testing for documentation

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. The accepted method of permeability testing is by ASTM Standard Test Method D5084, Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. Figure 10D–20 shows the equipment used for performing the test.

Contact the labs for more detailed information on documentation needed and for procedures for submitting samples.

If the only tests requested are gradation and Atterberg limit tests, smaller samples are needed. The size of sample that should be submitted depends on the gravel content. The following recommendations should be adhered to:

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).

If gradation analysis, Atterberg Limits, compaction and permeability testing are requested, considerably larger samples are required. When all these tests are needed, the sample size 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).

Submitting samples at their natural water content is important so designers can compare the natural water content to reference compaction test values. Samples should always be shipped in moisture proof containers for this reason. The best container for this purpose is a 5-gallon plastic pail commonly obtained in hardware stores. These pails have tight fitting lids with a rubber gasket that ensures maintenance of the water content in the samples during shipping. These 5-gallon pail containers are much more robust and less likely to be damaged during shipment than cardboard containers.

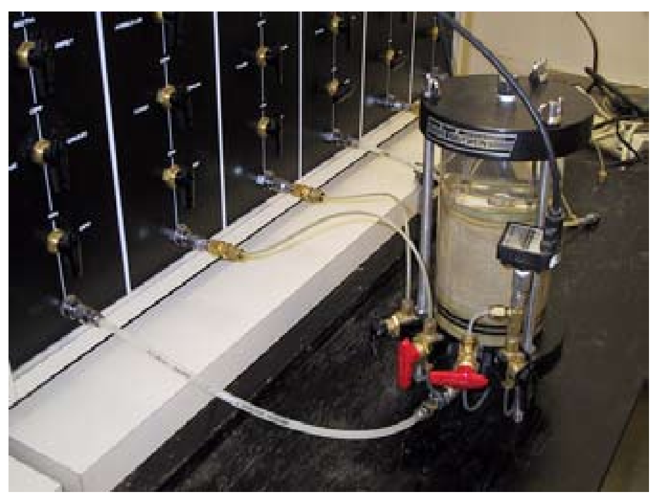
If designs rely on a minimum degree of compaction and water content to achieve stated permeability goals in a clay liner, testing of the clay liner during construction may be advisable to verify that design goals have been achieved. Field density and water content measurements are routinely made using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

Figure 10D–20 Equipment used for performing ASTM D5084

Molding a sample for a flexible wall permeability test

Molded sample after dissembling mold

Preparing sample in cell for flexible wall permeability test



Equipment for measuring permeability in flexible wall permeameter

Summary

- The reduction in the quantity of seepage that occurs as manure solids accumulate in the bottom and on the sides of storage ponds and treatment lagoons is well documented. However, manure sealing is not effective for soils with a low clay content. Figure 10D–21 shows a pond constructed in soils that were not suitable for manure sealing. Corrective action was needed because of the observed high seepage rates in these soils.
- To assume that manure sealing will be effective, a designer should ensure that the soils at grade have a minimum clay content (percent finer than 2 microns). A minimum clay content of 15 percent is required for one to assume that manure sealing will 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 No. 200 sieve) and plasticity index (PI). Soils in groups III and IV may be assumed to have a coefficient of permeability of 1×10^{-6} centimeters per second or lower unless they have an unusual clay chemistry (high calcium), or they have a very blocky structure. 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 desirable permeability rate can be achieved for a particular soil.
- If natural clay blankets are present at a site below planned grade of an excavated pond, the seepage rate should be estimated based on measured or estimated permeability values of layers beneath the liner and above an aquifer. If the estimated seepage rate is less than that given in NRCS guidance or state regulations, no special compacted liner may be required. If the soils at grade are not of sufficient thickness and permeability to produce a desirably low seepage rate, a liner should be designed to achieve the seepage rate that is the design goal.
- Guidance is given on factors to consider whether a constructed liner may be required. 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 appendix result in a somewhat conservative, but reasonable level of protection to important ground water resources. This guidance covers an area where may uncertainties exist, but where additional research will probably practice standards will be updated to reflect this state of the art knowledge.

Figure 10D–21 Old agricultural waste storage pond constructed before modern standards were placed in effect

References

Albrecht, B.A., and C.H. Benson. 2001. Effect of desiccation on compacted natural clays. *In* J. of Geotechnical and Geoenvironmental Engineering. pp. 67–75.

Barrington, S.F., and P.J. Jutras. 1983. Soil sealing by manure in various soil types. Paper 83–4571, ASAE, St. Joseph, MI. 28 pp.

Barrington, S.F., and P.J. Jutras. 1985. Selecting sites for earthen manure reservoirs. *In* Proc. of the 5th International Symposium on Agricultural Wastes, ASAE, St. Joseph, MI. pp. 386–392.

Benson, C.H., and G.P. Boutwell. 2000. Compaction conditions and scale-dependent hydraulic conductivity of compacted clay liners. *In* Constructing and Controlling Compaction of Earth Fills. ASTM STP 1384, D.W. Shanklin, K.R. Rademacher and J.R. Talbot, eds. American Society for Testing and Materials, West Conshohocken, PA.

Benson, C.H., and M. Othman. 1993. Hydraulic conductivity of compacted clay frozen and thawed *in situ*. *In* J. of Geotechnical Engineering, Amer. Soc. of Civil Eng. Vol 119, No. 2. pp. 276–294.

Benson, C.H., E.J. Chamberlain, A.E. Erickson, and X. Wang. 1995. Assessing frost damage in compacted clay liners. *In* ASTM Geotechnical Testing J., Vol. 18, No. 3. pp. 324–333.

Boutwell, G., and C.L. Rauser. 1990. Clay liner construction. Amer. Soc. of Civil Eng./Penn DOT Geotechechnical Seminar. Hershey, PA.

Brown, R.K. 1991. Construction practices and their impact on the quality of soil bentonite membranes. Workshop on Geotechnical Aspects of Earthen Agricultural Waste Structures, Natural Resources Conservation Service, Fort Worth, TX.

Daniel, D.E. 1984. Predicting hydraulic conductivity of clay liners. *In* J. of Geotechnical Engineering. Amer. Soc. of Civil Eng., Vol. 110, No. 2. pp. 285–300.

Daniel, D.E. 1987. Earthen liners for land disposal facilities. Proc. Geotech. Prac. for Waste Disp., Ann Arbor, MI. Amer. Soc. of Civil Eng. #19876. pp. 21–39.

Daniel, D.E. 1989. *In situ* hydraulic conductivity tests for compacted clay. *In* J. of Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 115, No. 9. pp. 1205–1226.

Daniel, D.E. 1993. Compacted clay liners and covers for arid sites. *In* J. of Geotechnical Engineering. Vol. 119, No. 2. pp. 223–237.

Daniel, D.E., and C.H. Benson. 1990. Water content-density criteria for compacted soil liners. *In* Journal of Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 116, No. 12. pp. 1811–1830.

Day, S.R., and D.E. Daniel. 1985a. Field permeability test for clay liners. ASTM STP 874. pp. 276–288.

Day, S.R., and D.E. Daniel. 1985b. Hydraulic conductivity of two prototype clay liners. *In* J. of Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 111, No. 8. pp. 957–990.

Elsbury, B.R., D.E. Daniel, G.A. Sanders, and D.C. Anderson. 1990. Lessons learned from compacted clay liner. *In* J. of Geotechnical Engineering. Amer. Soc. of Civil Eng., Vol. 116, No. 11. pp. 1641–1660.

Hermann, J.G., and B.R. Elsbury. 1987. Influential factors in soil liner construction for waste disposal facilities. Proc. Geotechnical Practice for Waste Disposal. Amer. Soc. of Civil Eng., Ann Arbor, MI. pp. 522–536.

Kim, W., and D. Daniel. 1992. Effects of freezing on hydraulic conductivity of compacted clay. *In* J. Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol. 118, No. 7.

Kleppe, J.H., and R.E. Olson. 1985. Desiccation cracking of soil barriers. ASTM Special Technical Publication 874, Hydraulic Barriers in Soil. Philadelphia, PA. pp. 263–275.

Lambe, T.W. 1958. The structure of compacted clay. *In* J. of the Soil Mechanics and Foundation Division, Amer. Soc. of Civil Eng., Vol. 84, No. Soil Mechanics 5, pp. 1654–1 to 1654–34.

Lehman, O.R., and R.N. Clark. 1975. Effect of cattle feedyard runoff on soil infiltration rates. J. Environ. Qual., 4(4):437–439.

Mitchell, J.K., D.R. Hooper, and R.G. Campanella. 1965. Permeability of compacted clay. J. Soil Mechanics and Foundation Div., Amer. Soc. of Civil Eng.. Vol. 91, No. 4. pp. 41–65.

Oakley, R. 1987. Design and performance of earth lined containment systems. Amer. Soc. of Civil Eng. Conf. Geotech. Prac. Waste Disposal, p. 117–136.

Othman, M., C. Benson, E. Chamberlain, and T. Zimmie. 1994. Laboratory testing to evaluate changes in hydraulic conductivity of compacted clays caused by freeze-thaw: state of the art, hydraulic conductivity and waste contaminant transport in soils, STP 1142. ASTM D. Daniel and S. Trautwein, eds. Philadelphia, PA. pp. 227–254.

Robinson, F.E. 1973. Changes in seepage rates from an unlined cattle waste digestion pond. Transactions ASAE, 16(1): 95–96.

Sowers, G. 1993. Discussion of effects of freezing on hydraulic conductivity of compacted clay, by W. J. Kim and D. Daniel [Vol. 118, No. 7]. *In* J. of Geotechnical Engineering, Amer. Soc. of Civil Eng., Vol 119, No. 11. pp. 1862-1864.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1994. Guide for determining the gradation of sand and gravel filters. National Engineering Handbook, Part 633, Chapter 26.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1991. Geology Note 5, Sample Size Requirements for Soil Mechanics Laboratory Testing.