

**Appendix 10D  
Design and Construction  
Guidelines for Waste  
Impoundments Lined with Clay or  
Amendment-Treated Soil**



## Appendix 10D

# Design and Construction Guidelines for Impoundments Lined with Clay or Amendment-Treated Soil

### 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, and
- thickness of low permeability horizons between the boundary of the lagoon bottom and sides and the distance to the aquifer or water table

In some circumstances, where permitted by local and/or State regulations, 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 research is that manure sealing is not effective unless soils have at least 15 percent clay content for monogastric animal generated waste and 5 percent clay content for ruminant animal generated waste (Barrington, Jutras, and Broughton 1987a, 1987b). Ma-

nure sealing is not considered effective on relatively clean sands and gravels, and these soils always require a liner as described in the following sections.

Animal waste storage ponds designed prior to about 1990 assumed that seepage from the pond would be minimized by the accumulation of manure solids and a biological seal at the foundation surface. Figure 10D-1 shows one of these early sites, where the soils at grade were somewhat permeable sands. Monitoring wells installed at some sites with very sandy soils showed that seepage containing constituents from the pond was still occurring even after enough time had passed that manure sealing should have occurred.

This evidence caused U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) engineers to reconsider guidance on suitable soils for siting an animal waste storage pond. In the late 1980s guidance was developed that designs should not rely solely on the seepage reduction that might occur from the accumulation of manure solids in the bottom and on the sides of the finished structure. That initial design document was entitled "South National Technical Center (SNTC) Technical Guide 716." It suggested that if any of four site conditions were present at a proposed structure location, a clay liner or other method of reducing seepage would be used in NRCS designs. A few revisions were made, and the document was re-issued in September 1993.

**Figure 10D-1** Animal waste storage pond constructed before the implementation of modern design guidelines



NRCS was reorganized in 1994, and guidance in old SNTC documents was not part of the revised document system of the Agency. Consequently, the 716 document was revised considerably, and the revised material was incorporated into appendix 10D of the Agricultural Waste Field Management Handbook (AWMFH) in October 1998. This 2008 version of appendix 10D continues to update and clarify the process of designing an animal waste storage pond that will meet NRCS-specified engineering design criteria and stated specified permeability requirements.

## General design considerations

Limiting seepage from an agricultural waste storage pond has two primary goals. The first is to prevent any virus or bacteria from migrating out of the storage facility to an aquifer or water source. The second is to prevent the conversion of ammonia to nitrate in the vadose zone. Nitrates are very mobile once they are formed by the nitrification process. They can then accumulate significantly in ground water. The National drinking water standard for nitrate is 10 parts per million, and excessive seepage from animal waste storage ponds could increase the level of nitrates in ground water above this threshold. Other constituents in the liquid manure stored in ponds may also be potential contaminants if the seepage from the pond is unacceptably high.

Defining an acceptable seepage rate is not a simple task. Appendix 10D recommends an allowable seepage quantity that is based on a historically accepted tenet of clay liner design, which is that a coefficient of permeability of  $1 \times 10^{-7}$  centimeters per second is reasonable and prudent for clay liners. This value, rightly or wrongly, has a long history of acceptability in design of impoundments of various types, including sanitary landfills. The seepage rate considered acceptable by NRCS is based on this permeability rate, also considering the following:

- When credit for a reduction of seepage from manure sealing (described later in the document) is allowed, NRCS guidance considers an acceptable initial permeability value to be  $1 \times 10^{-6}$  centimeters per second. This higher value used for design assumes that manure sealing will result in a tenth reduction in the

initial seepage. Other assumptions are that typical NRCS waste impoundments have a depth of liquid of about 9 feet and typical clay liners are 1 foot thick. The computed seepage rate before manure sealing took effect is then about 9,240 gallons per acre per day, and this rate would reduce to 924 gallons per acre per day when manure sealing reduced the seepage by one tenth. To introduce some conservatism into the design, the NRCS guidance allows a seepage rate of 5,000 gallons per acre per day for initial designs unless State or local regulations are more restrictive, in which case those requirements should be followed.

- If State or local regulations prohibit designs from taking credit for future reductions in seepage from manure sealing, then NRCS recommends the initial design for the site be based on a seepage rate of 1,000 gallons per acre per day, the approximate seepage predicted for a site with 9 feet of head, a 1-foot-thick clay liner and a coefficient of permeability in the liner of  $1 \times 10^{-7}$  centimeters per second. Applying an additional safety factor to this value is not recommended because it conservatively ignores the potential benefits of manure sealing.

One problem with basing designs on a unit seepage value is that the approach considers only unit area seepage. The same criterion applies for small and large facilities. More involved three-dimensional type analyses would be required to evaluate the potential impact of seepage on ground water regimes on a whole-site basis. In addition to unit seepage, studies for large storage facilities should consider regional ground water flow, depth to the aquifer likely to be affected, and other factors.

The procedures in appendix 10D to the AWMFH provide a rational approach to selecting an optimal combination of liner thickness and permeability to achieve a relatively economical, but effective, liner design. It recognizes that manipulating the permeability of the soil liner is usually the most cost-effective approach to reduce seepage quantity. While clay liners obviously allow some seepage, the limited seepage from a properly designed site should have minimal impact on ground water quality. Numerous studies, such as those done by Kansas State University (2000), have shown that waste storage ponds located in low permeability soils

of sufficient thickness have a limited impact on the quality of ground water.

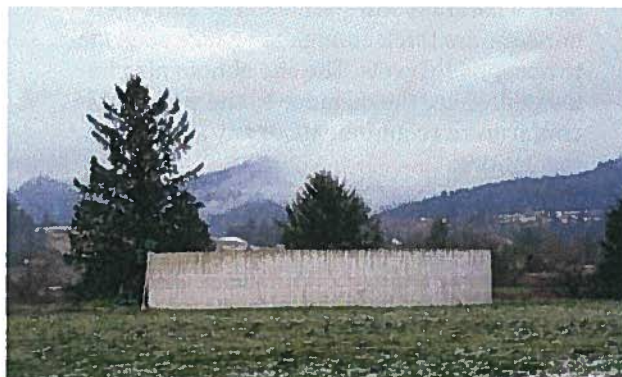
If regulations or other considerations cause a design to be devised with a goal of reducing unit seepage to less than 500 gallons per acre per day (1/56 inch per day), NRCS engineers' opinions are that synthetic liners such as high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), ethylene propylene diene monomer (EPDM), or geosynthetic clay liners (GCL), concrete liners, or aboveground storage tanks

will be required to achieve lower rates. Figure 10D-2 shows a pond lined with a synthetic liner, figure 10D-3 shows a concrete-lined excavated pond, and figure 10D-4 shows an aboveground concrete tank. Aboveground tanks may be also constructed of fiberglass-lined steel. NRCS has significant expertise in the selection, specification, and construction of sites using these products in addition to clay liners. Guidance on these other technologies is contained in other chapters of the AWMFH.

**Figure 10D-2** Pond with synthetic liner (Photo credit NRCS)



**Figure 10D-4** Aboveground storage tank for animal waste (Photo credit Mitch Cummings, Oregon NRCS)



**Figure 10D-3** Excavated animal waste storage pond with concrete liner (Photo credit NRCS)



## Progressive design

Waste storage ponds and waste treatment lagoons are usually designed with specific objectives that include cost, allowable seepage, aesthetics, and other considerations. Designs are usually evaluated in a progressive manner, with less costly and simple methods considered first, and more costly and complex methods considered next. 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 impoundment in soils that have a naturally low permeability and where horizons are thick enough to reduce seepage to acceptable levels. The site should also be located where the distance to the water table conforms to requirements of any applicable regulations.
- Soils underlying the excavated boundaries of the pond may not be thick enough or slowly permeable enough to limit seepage to acceptably low values. In this case, the next type of design often considered is a liner constructed of compacted clay or other soils with appropriate amendments. This type of liner may be constructed with soils from the excavation itself or soil may be imported from nearby borrow sources. If the soils require amendments such as bentonite or soil dispersants, the unit cost of the compacted liner will be significantly higher than for a liner that only requires compaction to achieve a satisfactorily low permeability.
- A synthetic liner may be used to line the impoundment to reduce seepage to acceptable levels. Various types of synthetic materials are available.
- A liner may be constructed of concrete, or a concrete or fiberglass-lined steel tank can be constructed above ground to store the wastes.

A useful tool in comparing design alternatives is to evaluate unit costs. Benefits of alternatives may then be compared against unit costs to aid in selecting a design alternative. Benefits may include reduced

seepage, aesthetics, or other considerations. 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, one should evaluate the volume of compacted fill involved in a liner of given thickness. Table 10D-1 illustrates a cost comparison for different thicknesses of compacted clay liners. If methods other than compacted clay liners are used, higher unit costs may apply (table 10D-2).

**Table 10D-1** Cost comparisons of design options for compacted clay liner

Thickness of compacted liner (ft)	Number of cubic yards of fill per square foot (yd <sup>3</sup> )	Assumed cost of compacted fill, per cubic yard (\$)	Unit cost of stated thickness liner (\$/ft <sup>2</sup> )
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

**Table 10D-2** Cost comparison for other design options

Liner type	Unit costs (\$/ft <sup>2</sup> )
Geosynthetic	0.50–1.25
Concrete, reinforced 5 inches thick	7.50–8.00



## Soil properties

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

- The percentage of the sample which is finer than the No. 200 sieve size, 0.075 millimeters. 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 the 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 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 structure creates preferential flow paths that can cause soils to have an unexpectedly high permeability. Albrecht

and Benson (2001) and Daniel and Wu (1993) describe the effect of desiccation on the permeability of compacted clay liners.

- While not considered in the USCS, the chemical composition of soils with clay content strongly affects 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, Clay Minerals, 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-3 is based on the percent passing the No. 200 sieve and PI of the soils. Table 10D-4 is useful to correlate the USCS groups to one of the four permeability groups.

**Table 10D-3** 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-4** Unified classification versus soil permeability groups <sup>1/</sup>

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

<sup>1/</sup> 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-5 shows an approximate range of estimated permeability values for each group of soils in table 10D-3. The ranges are wide because the classification system does not consider other factors that affect the permeability of soils, such as the electrochemical nature of the clay in the soils. Two soils may have similar percent finer than the No. 200 sieves 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 compared to those with a preponderance of calcium or magnesium. High calcium soils are more permeable than high sodium soils.

Table 10D-5 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. Information shown in figure 10D-5 is also valuable in gaining insight into the probable permeability characteristics of various soil and rock types.

Some soils in groups III and IV may have a higher permeability than indicated in table 10D-5 because they contain a high amount of calcium. High amounts of calcium result in a flocculated or aggregated structure in soils. These soils often result from the weathering

**Table 10D-5** 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	Estimated range of permeability, cm/s	
			Low	High
I	< 20	< 5	$3 \times 10^{-3}$	2
II	$\geq 20$	$\leq 15$	$5 \times 10^{-6}$	$5 \times 10^{-4}$
	< 20	$\geq 5$		
III	$\geq 20$	$16 \leq PI \leq 30$	$5 \times 10^{-8}$	$1 \times 10^{-6}$
IV	$\geq 20$	> 30	$1 \times 10^{-9}$	$1 \times 10^{-7}$



of high calcium parent rock, such as limestone. Soil scientists and published soil surveys are helpful in identifying these soil types.

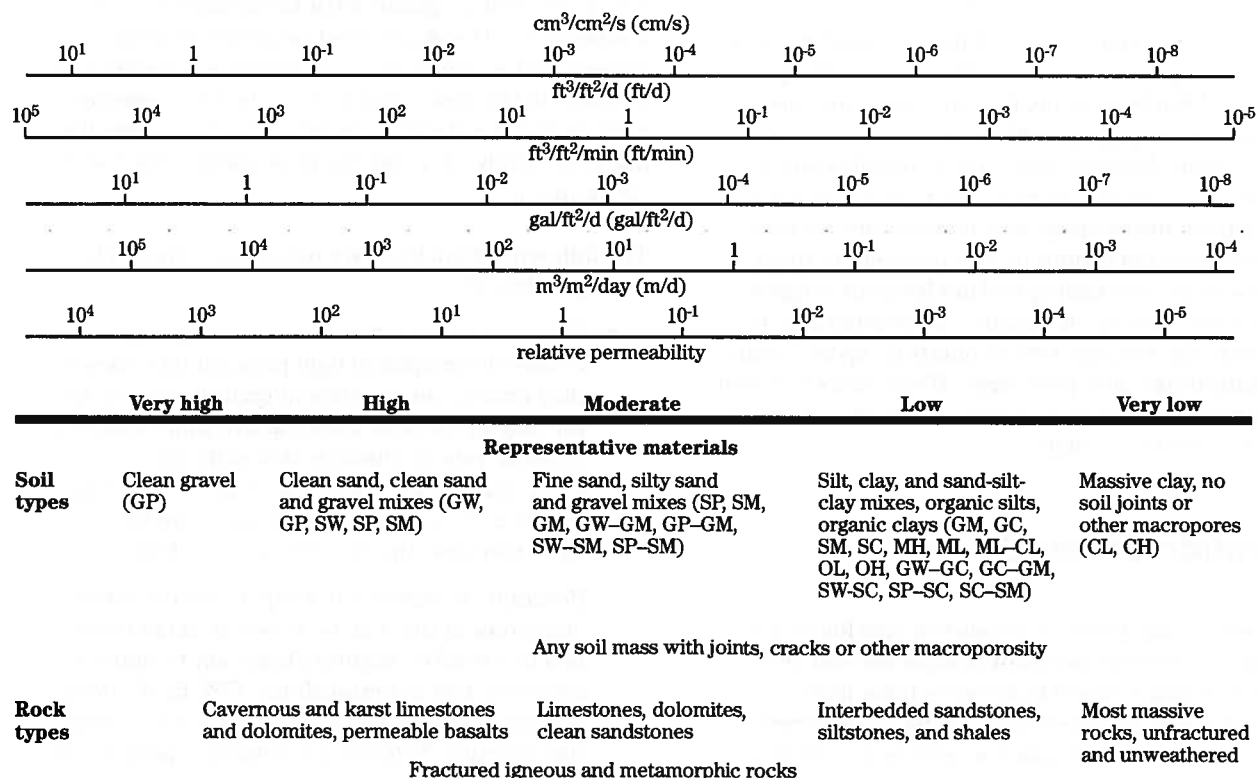
High calcium clays should usually be modified with soil dispersants to achieve the target permeability goals. Dispersants, such as tetrasodium polyphosphate, can alter the flocculated structure of these soils by replacement of the calcium with sodium. Because manure contains salts, it can aid in dispersing the structure of these soils, but design should not rely on manure as the only additive for these soil types.

Soils in group IV usually have a very low permeability. However, because of their sometimes blocky structure, caused by desiccation, high seepage losses can

occur through cracks that can develop when the soil is allowed to dry. These soils 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 recomacted 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.**

High plasticity soils like those in group IV should be protected from desiccation in the interim period between construction and filling the pond. Ponds with intermittent storage should also consider protection for high PI liners in their design.

**Figure 10D-5** Permeability of various geologic material (from Freeze and Cherry 1979)



## ***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 thickness 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 assumes that soils do not have 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:

- at least 2 feet of natural soil in groups III or IV occur below the bottom and sides of the lagoon
- the soils are not flocculated (high calcium)
- no highly unfavorable geologic conditions, such as karst formations, occur at the site
- the planned depth of storage is less than 15 feet

Ponds with more than 15 feet of liquid should be evaluated by more precise methods. If the permeability and thickness of horizons beneath a structure are known, the predicted seepage quantities may be estimated more precisely. In some cases, even though a site is underlain by 2 feet of naturally low permeability soil, an 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 up to 1 order of magnitude as noted previously. If regulations permit considering this reduction, a 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 the soil 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. 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, Pond Sealing or Lining Compacted Clay Treatment, addresses general design guidance for compacted clay liners for ponds.

If the available soils cannot be compacted to a density and water content that will produce an acceptably low permeability, several options are available, and described in the following section. The options involve soil additives to improve the permeability of the soils and adding liners constructed of materials other than natural soils.

**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. CPS 521C, Pond Sealing or Lining Bentonite Treatment, covers this practice. NRCS soil mechanics laboratories have found it important to use the same type

and quality of bentonite planned 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 will strongly 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. High calcium soils often occur when parent materials have excessive calcium. Many soils developed from weathering of limestone and gypsum 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 of concrete or synthetic materials such as geomembranes and geosynthetic clay liners (GCLs)**—Concrete has advantages and disadvantages for use as a liner. A disadvantage is that 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. An advantage is

that concrete serves as an excellent floor from which to scrape solids. It also provides a solid support for equipment such as tractors or loaders.

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 overlap is required to provide a seal at the seams. Geomembranes must contain ultraviolet inhibitors if exposed to sunlight. Designs should include provision for protection from damage during cleaning operations. Concrete pads, double liners, and soil covering are examples of protective measures. Figure 10D-6 shows an agricultural waste storage facility with a geomembrane liner with ultraviolet inhibitors.

## When a liner should be considered

A constructed liner may be required if any of the conditions listed are present at a planned impoundment.

**Proposed impoundment 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 impoundment 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 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 an impoundment 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.

**Figure 10D-6** Agricultural waste storage impoundment lined with a geomembrane (*Photo credit NRCS*)



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 an impoundment 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 one 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 an impoundment 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. 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.

These 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.

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 sinks or openings are known or identified during the site investigation, these areas should be avoided and the proposed facility located elsewhere. However, when these conditions are discovered during construction or alternate sites are not available, concrete or geosynthetic liners may be required, but only after the openings have been properly cleaned out and backfilled with concrete.

## Specific discharge

### Introduction

One way to require a minimal design at a site is to require a minimum thickness of a given permeability soil for a natural or constructed liner. An example of this would be to require that a clay liner constructed at a waste storage pond should be at least 1 foot thick, and the soil should have a coefficient of permeability of  $1 \times 10^{-7}$  centimeters per second or less.

However, using only permeability and thickness of a boundary horizon as a criterion ignores the effect of the depth of liquid on the predicted quantity of seepage from an impoundment. Using this approach would mean that the same design would be used for 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 for a unit area of the pond bottom.

A rational method of comparing design alternatives at a given site is needed. 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. This document presents methods for computing the term "specific discharge" to use in comparing alternatives and to document a given design goal for a site. Specific discharge is defined as unit seepage.

It does not reflect the total seepage from a site, but rather provides a value of seepage per square unit area of pond bottom.

This document uses calculations of specific discharge to compare design alternatives and to determine if a given design meets regulatory requirements and guidelines. In some cases, the total seepage from a pond may be of interest, particularly for larger ponds in highly environmentally sensitive environments.

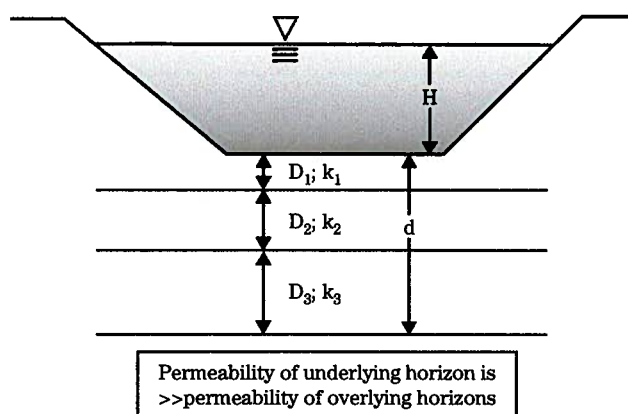
In those cases, more elaborate three-dimensional seepage computations using sophisticated finite-element computer programs may be warranted. It is outside the scope of this document to describe these types of analyses. Specialists who are experienced in using the complex software used for these computations should be consulted.

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.
- The depth of liquid in the pond—The depth of liquid at the top of the reservoir when pumping should commence is normally used.
- 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-7.

**Figure 10D-7** Conversion of permeability in layered profile to single value



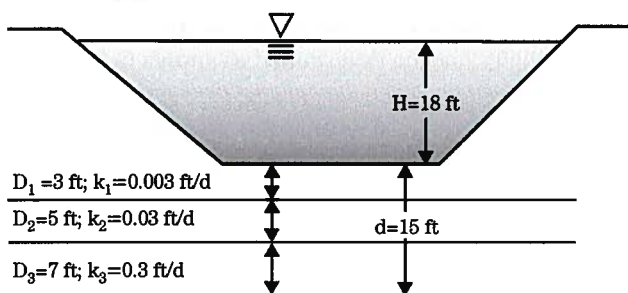
$$k_{\text{average}} = \frac{d}{\frac{D_1}{k_1} + \frac{D_2}{k_2} + \frac{D_3}{k_3}}$$

Example 10D-1 shows how to convert a multiple layer system into a single equivalent permeability. Using this method allows a designer to compute specific discharge when several horizons of constructed or natural soils occur below a site.

**Example 10D-1**

The excavated pond is underlain by 15 feet of soil consisting of three different horizons (fig. 10D-8). 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-8** Idealized soil profile for example 10D-1



**Solution**

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

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

**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.

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

For a pond with either a natural or constructed liner, the hydraulic gradient is the term  $i$  in the equation, and it is defined in figure 10D-9 as equal to  $(H+d)/d$ .

Given:

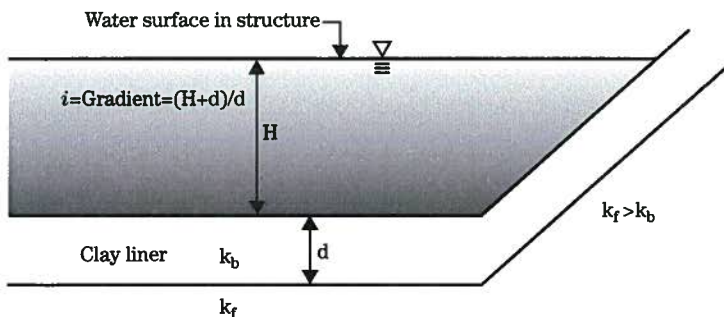
The Darcy’s law for this situation becomes:

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

where:

- $Q$  = total seepage through area  $A$  (L<sup>3</sup>/T)
- $k$  = coefficient of permeability (hydraulic conductivity) (L<sup>3</sup>/L<sup>2</sup>/T)
- $i$  = hydraulic gradient (L/L)
- $H$  = vertical distance measured between the top of the liner and top of the liquid storage of the waste impoundment (fig. 10D-9) (L)
- $d$  = thickness of the soil liner (fig. 10D-9) (L)
- $A$  = cross-sectional area perpendicular to flow (L<sup>2</sup>)
- $L$  = length
- $T$  = time

**Figure 10D-9** Definition of terms for clay liner and seepage calculations





Rearrange terms:

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

By definition, unit seepage or specific discharge, is  $Q \div A$ . The symbol  $v$  is used for specific discharge:

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

Specific discharge may be confused with 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 hydraulic gradient in a particular site, whereas specific discharge accounts for both permeability of the soil and the gradient causing the flow, as illustrated in figure 10D-9. Because hydraulic gradient is dimensionless, the units of specific discharge and permeability are then the same.

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 actual cross-sectional area of flow is computed by multiplying the soil cross section ( $A$ ) by the porosity ( $n$ ). The seepage velocity is then equal to the unit seepage or specific discharge,  $v$ , divided by the porosity of the soil,  $n$ . Seepage velocity =  $(v/n)$ . In compacted liners, the porosity usually ranges from 0.3 to 0.5. The result is that the average linear velocity of seepage flow is two to three times the specific discharge value. The units of seepage velocity are  $L/T$ .

To avoid confusion between 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  $1 \times 10^{-6}$  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,  $v$ . First, the coefficient of permeability may be converted to units of feet per day by multiplying the given units of centimeters per second by 2,835.

$$k = (5 \times 10^{-8} \text{ cm/s}) \times 2,835 = 0.000142 \text{ ft/d}$$

Then, the specific discharge  $v$  is computed as follows:

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

Conversion factors for specific discharge are given in table 10D-6.

**Table 10D-6** Conversion factors for specific discharge

To convert from	To units of	Multiply by
$\text{ft}^3/\text{ft}^2/\text{d}$	$\text{in}^3/\text{in}^2/\text{d}$	12
$\text{ft}^3/\text{ft}^2/\text{d}$	gal/acre/d	325,829
$\text{in}^3/\text{in}^2/\text{d}$	gal/acre/d	27,152.4
$\text{in}^3/\text{in}^2/\text{d}$	$\text{cm}^3/\text{cm}^2/\text{s}$	$2.94 \times 10^{-5}$
$\text{cm}^3/\text{cm}^2/\text{s}$	gal/acre/d	$9.24 \times 10^8$
$\text{cm}^3/\text{cm}^2/\text{s}$	$\text{in}^3/\text{in}^2/\text{d}$	34,015
$\text{cm}^3/\text{cm}^2/\text{s}$	$\text{ft}^3/\text{ft}^2/\text{d}$	2,835

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-6.

- 0.02 foot per day × 325,829 ≈ 6,500 gallons per acre per day
- 0.02 foot per day × 12 = 0.24 cubic inch per square inch per day

A variety of guidelines have been used and regulatory requirements stated for specific discharge. Usually, guidelines require the specific discharge for a given waste storage structure to be no higher than a stated value. The following example demonstrates the unit seepage that will result from a typical size animal waste storage lagoon or storage pond 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  $5 \times 10^{-8}$  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 follows, assuming:

- 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  $5 \times 10^{-8}$  centimeters per second
- Compute the specific discharge, *v*. First, the coefficient of permeability is converted to units of feet per day by multiplying the given units of centimeters per second by 2,835. Then,

$$k = (5 \times 10^{-8} \text{ cm/s}) \times 2,835 = 0.000142 \text{ ft/d}$$

Then, the specific discharge *v* is computed as follows:

$$\begin{aligned} v &= k \times \frac{H + d}{d} \\ &= 1.42 \times 10^{-4} \text{ ft/d} \times \frac{15 \text{ ft} + 2 \text{ ft}}{2 \text{ ft}} \\ &\approx 0.0012 \text{ ft}^3/\text{ft}^2/\text{d} \\ &\approx 0.0012 \text{ ft/d} \end{aligned}$$

Converting this into units of gallons per acre per day:

$$0.0012 \text{ ft/d} \times 325,829 \approx 393 \text{ gal/acre/d}$$

Table 10D-7 lists typical specific discharge values used by State regulatory agencies. Requirements vary from State to State. Individual designers may regard minimum requirements as too permissive. Some States permit a designer to assume that the initial computed seepage rate will be reduced 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.

### 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 documented 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 documented coefficient of permeability of  $1 \times 10^{-7}$  centimeters per second.

Clay liners may also be designed based on a stated allowable specific discharge value. Computations

**Table 10D-7** Typical requirement for specific discharge used by State regulatory agencies

Example specific discharge value	Equivalent value in gallons per acre per day
$1/56 \text{ in}^3/\text{in}^2/\text{d}$	485
$1/8 \text{ in}^3/\text{in}^2/\text{d}$	3,394
$1/4 \text{ in}^3/\text{in}^2/\text{d}$	6,788
$1 \times 10^{-6} \text{ cm}^3/\text{cm}^2/\text{s}$	924

may be performed as detailed in following sections to determine a design that will meet a design specific discharge goal.

## Detailed design steps for clay liners

The suggested steps for design of a compacted clay or amendment-treated liner are:

*Step 1*—Size the impoundment 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 greater. If natural low permeability horizons at least 2 feet thick or an equivalent thickness of soil with different permeability do not underlie the site, 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 soil may be imported from a nearby borrow source.

*Step 3*—Measure or estimate the permeability of the natural horizons or the compacted liner planned at the site. Use procedures shown in example 10D-1 to obtain a weighted permeability for the natural horizons.

*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. If State or local regulations provide a required value for allowable specific discharge, design on the basis of those regulations. Currently, State regulations for specific discharge range from a low of about 500 gallons per acre per day (1/56 inch per day) to a high of about 6,800 gallons per acre per day (1/4 inch per day). If no regulations exist, a value of 5,000 gallons per acre per day may be used. If a designer feels that more conservative limiting seepage is advisable, that rate should be used in computations. It is seldom technically or economi-

cally feasible to meet a design specific discharge value of less than 500 gallons per acre per day using compacted clay liners or amendment-treated soil liners. To achieve lower values of unit seepage usually requires synthetic liners, concrete liners, or aboveground storage tanks.

*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 in following sections to design a compacted clay liner or a liner with soil amendment.

### Notes to design steps:

- The calculated thickness of the soil liner required is sensitive to the relative values of soil permeability and the assumed allowable specific discharge value.
- The best and most economical way to reduce the required liner thickness is by reducing the soil's permeability. Liner permeability may be reduced by compacting soils to a higher degree, compacting them at a higher water content, and by using an appropriate additive such as bentonite or soil dispersants.
- By using higher compaction water contents and compacting soils to a high degree of saturation, permeability often can be reduced by a factor of 1/100.
- The liner soil must be filter compatible with the natural foundation upon which it is compacted. Filter compatibility is determined by criteria in NEH 633, 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 a liner is constructed directly on top of very coarse soil, such as poorly graded gravels and gravelly sands.
- 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.

- Clay liners constructed by mixing bentonite with the natural soils at a site should 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 a 7-inch thickness of compacted bentonite-treated liner is needed to meet suggested seepage criteria, the CPS 521C could dictate a thicker liner. That guidance should be considered in addition to the specific discharge computations.
- Natural and constructed liners must be protected against damage by mechanical agitators or other equipment used for cleaning accumulated solids from the bottom of the structure. 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 beneath the pond contains large, connected openings. Collapse of overlying soils into the openings could occur. 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. 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 times the liner is exposed. 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.

## Two methods for designing constructed clay liner

Two methods for designing a clay liner are available. In method A, designers begin with an assumed or required value for allowable specific discharge. Using the depth of liquid storage in the pond and known or estimated values of the liner's coefficient of permeability, a required thickness of liner is computed. If the value obtained is unrealistic, different values for the liner permeability are evaluated to determine what values produce a desirable thickness of liner. CPSs also determine minimum liner thicknesses.

In method B, designers begin with a desired thickness of liner and an assumed or required value for specific discharge. Using the depth of liquid storage in the pond and the desired thickness of liner, a required coefficient of permeability for the liner is computed. If the value obtained is unrealistic, different values for the liner thickness are evaluated to determine what values produce an achievable permeability. Coordinating with soil testing laboratories is helpful in evaluating alternatives that can provide the required permeability for the liner.

Each of these methods is illustrated with detailed design examples as follows:

**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. Terms have been previously defined.

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

**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 last equation. The reason is that the denominator would be zero, or a negative number. 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 consistent units. Note also that CPS 521D has requirements for minimum thickness of compacted clay liners. If the computed value for the required thickness is less than that given in CPS 521D, then the values in the CPS must be used.

### Example 10D-2—Design a clay liner using method A

#### Given:

Site design has 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  $6.5 \times 10^{-7}$  centimeters per second (0.00184 ft/d) 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 an eighth of an inch per day. Compute the required thickness of liner to be constructed of soil having 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 eighth of an inch per day specific discharge requirement into feet per day. To convert, divide an eighth by 12 to obtain a specific discharge requirement of 0.010417 foot per 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:

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

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

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

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:

$$10 \times (0.010417 \text{ ft/d}) = 0.10417 \text{ ft/d}$$

Substituting into the equation solving for thickness of liner required:

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

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

#### Conclusion:

A compacted clay liner this thin is impractical. In this case, the minimum thickness liner required in CPS 521D of 1 foot would be used for design.

**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. Terms have been previously defined.

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

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

### Example 10D-3—Designer a clay liner using method B

#### Given:

Site design has 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 guidance assumes that mature 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 using conversions shown in table 10D-6, 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:

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

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, v, of 0.0154 foot per day, then:

$$\begin{aligned} k &= \frac{.0154 \text{ ft/d} \times 1.5 \text{ ft}}{19 \text{ ft/d} + 1.5 \text{ ft}} \\ &= 1.1 \times 10^{-3} \text{ ft/d} \end{aligned}$$

Convert to centimeters per second by multiplying by 2,835.

$$\begin{aligned} k &= 1.1 \times 10^{-3} \text{ ft/d} \times 2,835 \\ k &= 4.0 \times 10^{-7} \text{ cm/s} \end{aligned}$$

*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-foot-thick liner may proceed with those recommendations.

## Construction considerations for compacted clay liners

### 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.

### Method of construction

Several methods are available for constructing a clay liner in an animal waste impoundment. Each has its advantages and disadvantages as described in following sections. A designer should consider the experience of local contractors and the relative costs of the methods in selecting the most appropriate design for a given site. The thickness of the planned soil liner, haul distance, planned side slopes for the pond, and other factors also guide a designer's decision on the best method to use.

### Bathtub construction

This method of construction consists of a continuous thickness of soil compacted up and down or across the slopes. Figure 10D-10 shows the orientation of the lifts of a compacted liner constructed using this method, as contrasted to the stair step method, which is covered next. Figure 10D-11 shows two sites where the bathtub method of construction is being used.



This construction method has the following advantages over the stair-step method:

- The layers of compacted clay are oriented perpendicular to flow through the liner in this method. If the lifts making up the liner are not bonded well, the effect on seepage is minor, compared to the stair-step method.
- This method lends itself to constructing thinner lifts, which is more economical.

The bathtub construction method has the following disadvantages compared to the stair-step method:

- Side slopes must be considerably flatter than for the stair-step method, creating a pond with a larger surface area. A pond with a larger surface area has to store more precipitation falling on it, which could be considered an extra cost of the method.
- To permit equipment traversing up and down the slopes, slopes must be an absolute minimum of 3H:1V. Shearing of the soil by the equipment on steeper slopes is a concern. 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.

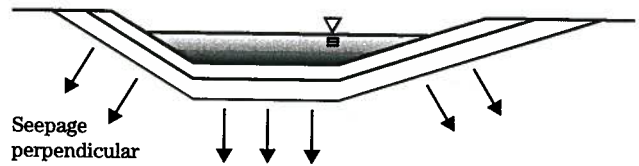
### Stair-step construction

The stair-step method of construction is illustrated in figure 10D-10. Construction of the liner consists of compacting lifts of soil around the perimeter of the liner in a stair-step fashion, finishing the job by shaving off some of the side liner and placing it in the bottom of the pond. This method of construction is required if the side slopes of the pond are any steeper than about 3H:1V. Advantages of this method of construction are:

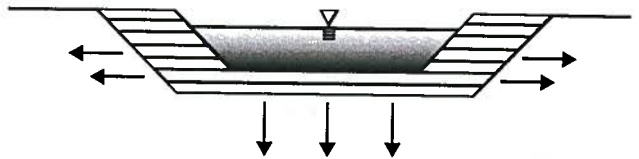
- A thicker blanket, measured normal to the slope, will result compared to the bathtub method of construction (fig. 10D-10). This is a positive factor in seepage reduction.
- It allows steeper side slopes, and thus the surface area of the pond exposed to rainwater accumulation is smaller than a bathtub construction would permit.
- The thicker blanket reduces the impact of shrinkage cracks, erosive forces, and potential mechanical damage to the liner.

**Figure 10D-10** Methods of liner construction (after Boutwell 1990)

#### Bathtub construction



#### Stair-step construction



**Figure 10D-11** Bathtub construction of clay liner (photo courtesy of NRCS Virginia (top) and NRCS Nebraska (bottom))



- Ponds constructed with this method are deeper for a given volume of waste than ponds constructed with the bathtub method, which favors anaerobic processes in the pond.

Disadvantages of the method are:

- This method may be more expensive than the bathtub method because the liner on the sides of the pond are thicker.
- Flow is parallel to the orientation of the layers forming the compacted liner on the pond sides. If care is not taken to obtain good bonding between lifts, seepage through the interface between lifts could be higher than expected.
- Contractors may be less familiar with this method of operation of equipment.

In the stair-step method of construction, the pond is first excavated. Borrow soil is then imported with a truck or scraper and spread in thin lifts (8 to 9 in thick) prior to compaction. Figure 10D–12a 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–12b). The interior liner is constructed by bringing up lifts the full depth of the pond. Photo 10D–12c 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 (fig. 10D–12c).

### Soil type

Soils in groups III and IV are the most desirable for constructing a clay liner (table 10D–3). 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.

### 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 exces-

**Figure 10D–12** Stair-step method (Photo credit John Zaginaylo, PA, NRCS)

(a)



(b)



(c)





sively 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 result in an increase in permeability of the liner. A protective layer of lower PI soils is often specified for protection of higher PI clay liners to prevent this problem from developing.

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 this problem.

### 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-13 shows the structure that results from compacting soils containing clods that are not adequately broken down.

### 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 for a given soil. If soils are too dry, they cannot effectively be compacted to a condition where their structure is acceptable and their permeability may be higher than desirable. Compacting a soil at the proper water content creates 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 yard of compacted soil by 1 percent.

### Dry conditions in the borrow

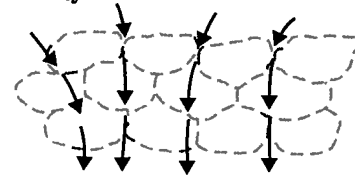
If soils in the borrow area are dry, several problems may need to be addressed. If the soils are clays with relatively high plasticity (PI values greater than about 20), they are likely to be very cloddy when excavated.

Water is slow to penetrate the clods and compaction is less likely to degrade clods if enough time has not elapsed between adding the water and compaction. More descriptions follow in subsequent sections, and figure 10D-13 illustrates how clods left in the compacted fill will likely cause the soil to have a higher than expected permeability.

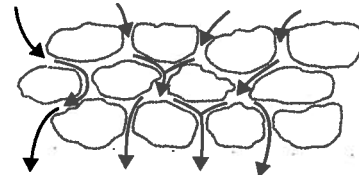
If the water content of borrow soils is more than 3 or 4 percent drier than required for specified compaction conditions, consideration should be given to wetting the soils in the borrow prior to construction. Adding large amounts of water during processing on the fill is

**Figure 10D-13** Macrostructure in highly plastic clays with poor construction techniques (from Hermann and Elsbury 1987)

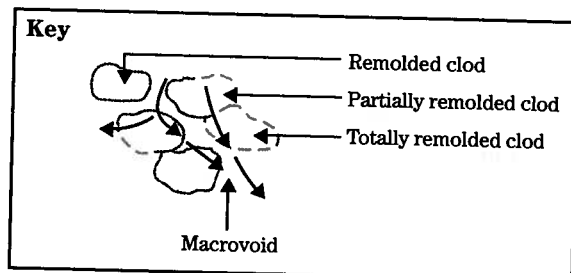
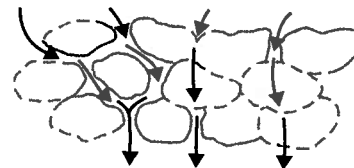
#### Micropermeability



#### Macropermeability



#### Intermediate situation



difficult and inefficient. Sprinklers can be set up in the borrow some time before construction is planned and then time will allow water to soak into the soils more thoroughly.

### 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, which assumes that the highest degree of saturation achievable is 90 percent:

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

where:

$w_n$  (%) = natural water content of borrow soils, %  
 $G_s$  = specific gravity of the soil solids (dimensionless)

Specific gravity values are obtained by ASTM Standard Test Method D854. An average value for specific gravity is often assumed to be 2.68. However, soils with unusual mineralogy may have values significantly different. Soils with volcanic ash may have specific gravity values as low as 2.3, and soils with hematite in them may have values as high as 3.3, based on NRCS laboratory results.

*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. 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 evaluate whether a lower degree of compaction will result in an acceptable permeability value.

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 by only disking is somewhat ineffective, and it is difficult to reduce their water content by more than 2 or 3 percent with normal effort. It may be more practical to delay construction to a drier part of the year when the borrow source is at a lower water content. In some cases, the borrow area can be drained several months before construction. This would allow gravity drainage to decrease the water content to an acceptable level.

*Step 5* 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:

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

### 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 soil. 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 was 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 were measured.

*Solution:*

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?

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

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

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 how wet the sample could be and still 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:

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

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

This computation confirms 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.

## Methods of excavating and processing clay for liners

### Clods in borrow soil

If borrow soils are plastic clays at a low water content, the soil will probably have large, durable clods. Disking may be effective for some soils at the proper water content, but pulverizer machines may also be required. To attain the highest quality liner, the transported fill should be processed by adding water and then turned with either a disk or a high-speed rotary mixer before using a tamping roller. Equipment requirements depend on the strength and size of clods and the water content of the soil.

### Placement of lifts

Individual lifts of soil usually consist of an equipment width (often about 8 to 10 feet wide) layer of soil about 6 inches thick, after compaction. These lifts should be staggered to prevent preferential flow along the inter-lift boundaries. Figure 10D-14(a) shows the preferred way of offsetting the lifts. Figure 10D-14(b) shows a method that should be avoided. Bonding between the 6-inch lifts is also important so that if water does find its way down the boundary between two lanes of compacted soil that it cannot flow laterally and find the offset boundary.

## 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-14** Construction methods to limit interlift preferential flow paths

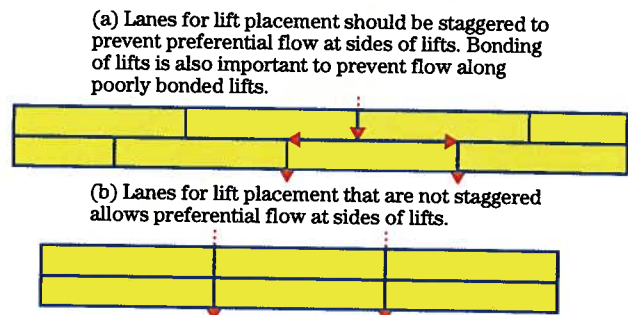


Figure 10D-13 illustrates the structure that can result from inadequate wetting and processing of plastic clay. The permeability of intact clay particles may be quite low, but the overall permeability of the mass is high because of flow between the intact particles.

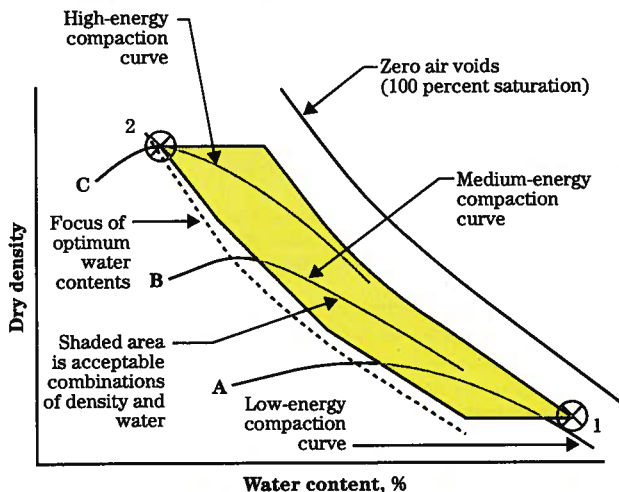
### Dry density and optimum water content

Compaction specifications for most earthfill 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 and Benson 1990). Figure 10D-15 illustrates a window of compacted dry density and water content in which a given permeability could be obtained for an example soil. The principles involved can be illustrated as follows.

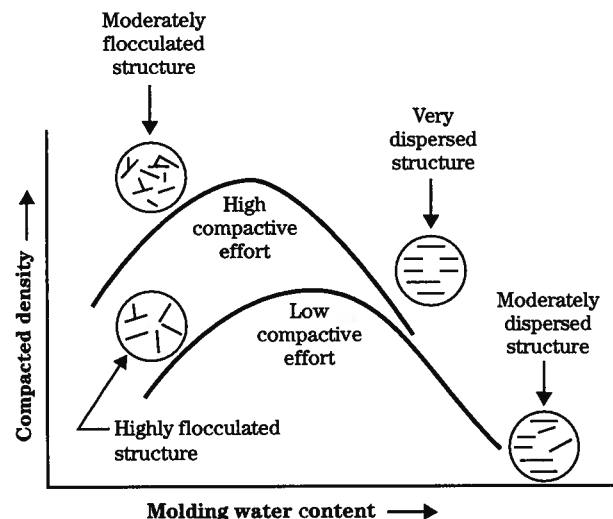
Assume that a given soil is being used to construct a clay liner for an animal waste impoundment. A moderately plastic silty clay classifying as CL in the USCS is used. In case 1, the soil being obtained from a nearby borrow area has a relatively high natural water content. The contractor elects to use 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-15. 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. This time 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-15.

Laboratory tests can be used to establish the boundary conditions and arrive at a window of acceptable densities and water contents for a clay liner. Figure 10D-16 shows how a different structure results between soils compacted wet of optimum and those compacted dry of optimum water content. It also illustrates that soils compacted with a higher compactive effort or energy have a different structure than those compacted with low energy.

**Figure 10D-15** Range at acceptable moisture/density for a typical clay liner



**Figure 10D-16** Effect of water content and compactive effort on remolding of soil structure in clays (from Lambe 1958)





Mitchell (1965) was instrumental in explaining how the permeability of clay soils is affected by the conditions under which they were compacted. Figure 10D-17 illustrates 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 higher 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.

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 relatively high for water contents less than optimum.

Lambe (1958) explains how the energy used and the water content of the soil at the time of compaction affect the permeability of the soil by creating structure in the soil. Figure 10D-16 summarizes his explanation

of how different soil structures results from these two factors. Soils compacted with higher energy (heavier equipment and numerous passes of the equipment) at a higher water content have a dispersed structure. This structure creates very small plate-shaped voids that are resistant to water flow. Soils that are compacted with lower energy and/or lower water contents have a flocculated structure. This structure involves larger voids that are more conducive to water flow.

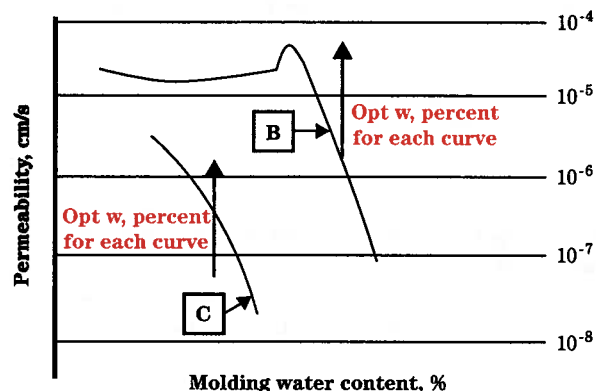
### Percent saturation importance

Benson and Boutwell (2000) studied the correlation between field measured permeability values on compacted liners with laboratory measured values. The study 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. The study 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 than done with field compaction procedures.

The conclusions of Benson and Boutwell's research were 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 apply.

- Soils should generally be compacted wet of the line of optimums. The line of optimums is illustrated in figure 10D-15. It is the locus of optimum water content values for a given soil for a range of compactive energy. A soil compacted with a low energy (like that resulting from a small sheepsfoot roller), curve A in figure 10D-15, will have a relatively low maximum density and high maximum water content. A soil compacted with a high energy (like that resulting from using a large heavy tamping roller), curve C in figure 10D-15, will have a high value for maximum density and a low value of optimum water content. The line of optimums is the locus of points connecting the values of optimum water content. Remember that optimum water content depends on the energy used and that Standard Proctor (ASTM D698) is only one standard type of compaction

**Figure 10D-17** Plot showing effect of molding water content on permeability (Mitchell 1965)



test. ASTM D1557, the modified energy test is also used for design of some clay liners.

- Eighty percent of field tests of dry density and water content should plot to the right of the line of optimums if the field permeability is expected to reflect the same values obtained in laboratory testing.
- The average water content of all quality control tests should be from 2 to 4 percent wetter than the line of optimums as defined.

## 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 varies with 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 should be heavy enough to cause the projections (teeth or pads) on the roller to penetrate or almost penetrate the compacted lift. Enough passes must be used to attain coverage and break up any clods. Additional passes do not compensate for rollers that are too light.

Roller size is often specified in terms of contact pressure exerted by the feet on sheepsfoot or 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.

## Equipment considerations

### Size and shape of teeth on roller

Older style sheepsfoot-type projections on rollers are best suited for compacting clay soils to achieve the lowest possible permeability. They are better suited than the modern style rollers called tamping rollers that have more square, larger area projections. The longer teeth on the older style sheepsfoot rollers are better at remolding plastic clay soils that are wet of optimum water content, and they are better at degrading clods in the soils (fig. 10D–18). The modern tamping-type rollers are effective in compacting soils at a drier water content when high bearing capacity is needed, like soils being compacted for highway subgrades (fig. 10D–19). The older style of sheepsfoot roller compactors are better suited for compaction to achieve low permeability.

### 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 projections. Many modern rollers are too heavy to compact soils that are more than 1 or 2 percent wet of optimum water content. When the specified compaction water content is 2 percent or more wet of optimum water content, lighter rollers are essential. Permeability of clays is minimized by compaction at water contents wet of optimum.

### Speed of operation

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

### Vibratory versus nonvibratory sheepsfoot and tamping rollers

Some sheepsfoot and tamping rollers have an added feature, a vibratory action. This feature can usually be activated or deactivated while soils are being compacted. Vibratory energy adds little to the effectiveness

of these rollers when the soils being compacted are clays. At the same time, the vibration of the equipment is not usually detrimental. One condition in which the vibratory energy of this type of equipment might be detrimental is when a clay liner is being constructed on a subgrade of low plasticity silts or sands that are saturated. The vibration of the equipment often causes these types of foundation soils to become dilatant as they densify, and the water expelled in this process can create a trafficability problem. For this reason, when subgrade soils are saturated low plasticity silts and sands, the vibratory action of the compaction equipment should be disabled.

### Vibratory smooth-wheeled rollers

Vibratory smooth-wheeled rollers are well suited to compacting bentonite-treated liners. They should not be used for compacting clay liners, however. The smooth surface of the roller results in poor bonding between lifts and can cause problems like those shown in figure 10D-14. The load distribution of the rollers also causes the top of a lift to be compacted well but the bottom of the lift not as well, when fine-grained soils are being compacted. A vibratory smooth-wheeled roller is shown in figure 10D-20.

**Figure 10D-18** Longer style of teeth preferable for compacting soils for clay liner



**Figure 10D-20** Smooth-wheeled steel roller compactor



**Figure 10D-19** Modern type of tamping roller less well suited for compacting soils for clay liner



## Freeze-thaw and desiccation

### 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). Freeze-thaw damage is more likely to affect the side slopes of a clay-lined pond than it will the bottom of the pond after it is filled. If freeze-thaw damage is regarded as likely to increase the permeability of the soils on the side slopes of the pond, a thicker liner or protective cap of cover soil should be considered. The extra cost of freeze-thaw protection may cause a designer to consider a synthetic liner alternative for reasons of economy and confidence in the low permeability of the synthetic liner. For instance, Minnesota designs often include the use of GCL liners for this reason.

### 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. 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, those with PI values of 30 or higher.

## Design and construction of bentonite amended liners

When soils at grade of an excavated pond are low plasticity sands and silts in groups I or II of table 10D–3, an unlined pond will result in unacceptably high seepage losses. Several design options are normally considered for this situation. The options are listed as follows in order of increasing cost:

- Clay soils suitable for a clay liner are located in a nearby borrow area and imported to the site to construct a compacted clay liner. CPS 521D applies to this practice.
- Soils from the excavation and at the excavated subgrade are treated with bentonite to create a compacted liner with the required permeability and thickness. CPS 521C applies to this practice.
- The pond may be lined with geosynthetic, a GCL, or lined with concrete. An aboveground storage tank is also an option.

## Bentonite type and quality

Several types of bentonite are mined and marketed for use in treating soils to produce a low permeability liner. The most effective type of bentonite (less volume required per cubic foot of treated soil) is finely ground sodium bentonite that is mined in the area of northeast Wyoming, southeast Montana, and western South Dakota. This sodium bentonite is derived from weathered volcanic ash. Sodium bentonite is a smectite clay composed primarily of the mineral montmorillonite (Bentofix 2007). It has the ability to swell up to 10 to 15 times its dry natural volume when exposed to water. Other types of bentonite, usually calcium bentonite are also mined and marketed for treating soils. These types of bentonites are less active (less free swell potential) and more volume of bentonite per treated cubic yard of soil will be required to produce a target permeability than would be required if sodium bentonite were used.

Two methods of evaluating a bentonite source being considered for use as an additive for a liner has high swell properties exist. They are:

- Determine the level of activity based on its Atterberg limit values as determined in a soil testing laboratory. High-quality sodium bentonite has LL values greater than 600 and PI values greater than 550.
- High-quality sodium bentonite has a free swell value of 22 milliliter or higher, based on experience of NRCS engineers and generally accepted guidance. An ASTM Standard test method to evaluate the free swell potential of bentonite is used to verify the quality of bentonite used



in GCL liners and is also suitable for evaluating bentonite proposed for a liner being constructed using CPS 521C. The ASTM method is D5890. A summary of the method follows.

- Prepare a sample for testing that consists of material from the total sample that is smaller than a No. 100 sieve.
- Partially fill a 100-milliliter graduated cylinder with 90 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. Wash the sides of the cylinder and fill to the 100-milliliter level.
- After 2 hours, inspect the hydrating bentonite column for trapped air or water separation in the column. If present, gently tip the cylinder at a 45-degree angle and roll slowly to homogenize the settled bentonite mass.
- After 16 hours from the time the last of sample was added to the cylinder, record the volume level in milliliters at the top of the settled bentonite. Record the volume of free swell, for example, 22 milliliters free swell in 24 hours.

Figure 10D-21 shows an excellent quality bentonite reaction to the test. It has a free swell of about 27 milliliters.

**Figure 10D-21** Free swell test for bentonite ASTM D5890



Bentonite is furnished in a range of particle sizes for different uses. Fineness provided by the bentonite industry ranges from very finely ground, with most particles finer than a No. 200 sieve, to a granular form, with particles about the size of a No. 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 use in construction the same quality and fineness as was used by the soils laboratory for the permeability tests to arrive at recommendations. Fineness for use in treating liners for waste impoundment can also be specified by an acceptable bentonite by supplier and designation, or equivalent. An example specification is Wyo Ben type Envirogel 200, CETCO type BS-1, or equivalent.

### Design details for bentonite liner

The criteria given in CPS 521C, Pond Sealing or Lining, Bentonite Treatment, provide minimum required liner thicknesses for various depth of liquids.

CPS 521C provides guidance on rates of application of bentonite for preliminary planning purposes or where the size and scope of the project does not warrant obtaining samples and having laboratory tests performed. These preliminary recommended rates of application are based on using high-quality sodium bentonite that is finely ground. The CPS 521C includes a table that shows a range of recommended application rates which vary with the type of soil being treated. Higher rates of application are needed for coarse, clean sands and lower rates for silts. The table shows a recommended application rate expressed in pounds of bentonite per square foot per inch of liner to be built. For example, a typical rate of application for a relatively clean sand would be about 0.625 pounds per square foot per inch of compacted bentonite-treated liner. The most up-to-date CPS 521C should always be consulted for recommended rates, in case they have changed since this document was written.

For planning purposes, using these recommended rates, the amount of bentonite needed for a job can be estimated. For example, assume that a pond is to be constructed with an area of the sides and bottom totaling one acre. Assume that considering the planned depth of water in the pond, a design has been formu-

lated that calls for a 1-foot-thick bentonite-treated liner and that an application rate of 0.625 pounds per square foot per inch is needed. The total amount of bentonite required per square foot will be

$$0.625 \text{ lb/ft}^2 \times 12 \text{ in/ft} = 7.5 \text{ lb}$$

of bentonite per square foot. For an acre of pond area, the total amount needed will be

$$\begin{aligned} 7.5 \text{ lb/ft}^2 \times 43,560 \text{ ft}^2/\text{acre} &= 326,700 \text{ lb} \\ &= 163 \text{ tons} \end{aligned}$$

The cost of bentonite is affected strongly by freight, and the further a site is from the area of the United States where bentonite is produced, the more costly it will be. Better unit prices are available for larger quantities.

Remember that the preliminary rates of application provided in CPS 521C assume that finely ground high-swell sodium bentonite is used. If plans anticipate that a lower quality bentonite with a free swell less than about 22 milliliters or a coarsely ground bentonite may be used, laboratory testing is required to establish a rate of application that will create a suitably low permeability. Design using the specific discharge approach will establish what the target permeability value should be.

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 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 compac-

tion, 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 results of step 5.

### Example 10D-5—Design of a bentonite-treated liner

*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. Assume the current CPS requires a liner that is 18 inches thick (1.5 ft).

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, use conversion values shown in table 10-6, multiply:

$$v = \frac{1}{56} \text{ in/d} \times 2.94 \times 10^{-5} = 5.25 \times 10^{-7} \text{ cm/s}$$

The thickness of the liner and depth of liquid in the pond must also be converted to metric units. 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,  $H$ , of 21 feet is equal to

$$H = 21 \text{ ft} \times 12 \text{ in/ft} \times 2.54 \text{ cm/in} = 640.1 \text{ cm}$$

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

$$\begin{aligned} k &= \frac{v \times d}{H + d} \\ k &= \frac{5.25 \times 10^{-7} \text{ cm/s} \times 45.72 \text{ cm}}{640.1 \text{ cm} + 45.72 \text{ cm}} = 3.5 \times 10^{-8} \text{ cm/s} \end{aligned}$$



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  $5 \times 10^{-8}$  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.

### Considerations for protective cover

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 thinner than compacted clay liners. Because the liner is thin, it can be more easily damaged by erosion from rainfall and runoff while the pond is empty. Rills in a thin liner provide a direct pathway for seepage.
- 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.

### Construction specifications for bentonite liner

The best equipment for compacting bentonite-treated liners is smooth-wheeled steel rollers, as shown in figure 10D–20. 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 high-speed rotary mixer is the best method of obtaining the desired mix (fig. 10D–22). A minimum of two passes of the equipment is recommended to assure good mixing. When multiple passes of equipment are used for applying and mixing the bentonite, the passes should be in directions perpendicular to each other. This encourages a more homogeneous mixture.

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

Depending on the type of equipment used, tearing of the liner during compaction can occur on slopes of 3H:1V or steeper. Compacting along, rather than up and down slopes, could be unsafe on 3H:1V or steeper side slopes. For most sites, slopes of 3.5H:1V or 4H:1V should be considered.

**Figure 10D–22** Pulvermixer (high-speed rotary mixer)  
(Photo credit Stacy Modelski, NRCS)



Bentonite-treated liners are often constructed in lifts that are 4-inch compacted thickness. 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 excavation. 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.

## Design and construction of clay liners treated with soil dispersants

Previous sections of this appendix caution that soils in groups III and IV containing high amounts of calcium may be more permeable than indicated by the percent fines and PI values. Groups III and IV soils predominated by calcium usually require some type of treatment to serve as an acceptable liner. The most common method of treatment to reduce the permeability of these soils is use of a soil dispersant additive containing sodium.

### Types of dispersants

The dispersants most commonly used to treat high calcium clays are soda ash ( $\text{Na}_2\text{CO}_3$ ) and polyphosphates. The two most common polyphosphates are tetrasodium pyrophosphate (TSPP), and sodium tripolyphosphate (STPP). Common salt ( $\text{NaCl}$ ) has been used in the past, but it is considered less permanent than other chemicals and is not permitted in the current CPS 521B. NRCS experience has shown that usually about twice as much soda ash is required to effectively treat a given clay when compared to the other two dispersants. However, because soda ash is often less expensive, it may be the most economical choice in many applications.

### Design details for dispersant-treated clay liner

CPS 521B, Pond Sealing or Lining, Soil Dispersant, provides minimum thicknesses of liners 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 per 100 square feet for each 6-inch layer of liner. The total amount of dispersant per 100 square feet is then equal to the number of 6 inch lifts in the completed liner multiplied by the rate per lift.

### Example 10D-6—Steps in design of a dispersant-treated liner

Assume for the purposes of this example that a soil has been tested at a site and found to be a flocculated clay with an unacceptably high permeability. The designer chooses to evaluate a soda ash-treated liner. Consult the current CPS 521B for guidance on application rates for soda ash. Assume that the current CPS suggests an application rate of 15 pounds of soda ash per 100 square feet of liner for each 6-inch-thick lift of finished liner. Next, assume that based on the depth of water in the pond that the CPS 521B requires a total liner thickness of 12 inches. Then, because each 6-inch-thick lift requires 15 pounds of soda ash per 100 square feet, the total amount of soda ash required for this example would be 30 pounds of soda ash per 100 square feet. The most up-to-date CPS 521B should always be consulted for recommended rates, in case they have changed since this document was written.

The recommended rates of application of dispersants in CPS 521B are based on the most up-to-date information from the NRCS soils testing laboratories. The rates are in general conservative, and if a designer wanted to evaluate lower rates of application, samples should be obtained and sent to a laboratory for documenting the efficacy of lower rates. If this procedure is followed, the following steps are usually implemented.

*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* A standard Proctor (ASTM D698) test is performed to determine the maximum dry density and optimum water content.

*Step 3* From the preliminary design of the site, determine the depth of water in the structure and 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 results from previous steps.

### Example 10D-7—Comprehensive example for a dispersant-treated liner

#### 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. Assume that the current CPS 521B requires a minimum liner thickness of 1.5 feet. The example problem is to determine what permeability is required to meet the stated specific discharge requirement.

#### Solution:

First, the required specific discharge value, which is given in units of gallons per acre per day has to be converted the same units that will be used for required permeability. Assume that permeability will be expressed in centimeters per second, so use table 10D-6 to convert the value of 2,000 gallons per acre per day to centimeters per second as follows:

$$v = \frac{2,000 \text{ gal/acre/d}}{9.24 \times 10^8} = 2.2 \times 10^{-6} \text{ cm/s}$$

Next, convert the liner thickness and depth of liquid from units of feet to centimeters:

$$d = 18 \text{ in} \times 2.54 \text{ cm/in} = 45.72 \text{ cm}$$

$$H = 18 \text{ ft} \times 12 \times 2.54 \text{ cm/ft} = 548.64 \text{ cm}$$

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

$$\begin{aligned} k &= \frac{v \times d}{H + d} \\ &= \frac{2.2 \times 10^{-6} \text{ cm/s} \times 45.72 \text{ cm}}{548.64 \text{ cm} + 45.72 \text{ cm}} \\ &= 1.7 \times 10^{-7} \text{ cm/s} \end{aligned}$$

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  $5 \times 10^{-8}$  centimeters per second. A designer should proceed with this design specifying the application rate recommended by the soils lab and a 1.5-foot-thick liner to obtain the design specific discharge.

### Construction specifications for a 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 a disk, high speed rotary mixer, or similar equipment. Because small quantities of soil dispersants are commonly used, uniform mixing of the dispersants is essential to constructing an effective liner. If a standard disk plow is used, several passes should be specified. A high-speed rotary mixer is also essential to obtain a thorough mixture of the dispersant with the clay being amended. Figure 10D-23 shows this type of equipment. At least two passes of the equipment is recommended to assure good mixing.

Other construction considerations are also important. Using the bathtub method of construction on slopes of 3H:1V or steeper can cause tearing of the liner during compaction and reduce the effectiveness of compaction equipment. Slopes as flat as 3.5H:1V or 4H:1V should be considered for this factor alone, for bathtub type construction.

Current CPSs usually require a liner thicker than 6 inches. A liner generally can be satisfactorily constructed in a series of lifts 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.

**Figure 10D-23** High-speed rotary mixer used to mix dispersants into clays (Photo credit Jody Kraenzel, NRCS)



## Uplift pressures beneath clay blankets

A clay blanket may be subject to uplift pressure from a seasonal high water table in the foundation soil underneath the clay liner. The uplift pressure in these cases can exceed the weight of the clay liner, and failure in the clay blanket can occur (fig. 10D-24). This problem is most likely to occur during the period before the waste impoundment is filled and during periods when the impoundment may be emptied for maintenance and cleaning. Figure 10D-25 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 to attain a satisfactory safety factor should be used if they are required.

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:

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

where:

- d = thickness of liner, measured normal to the slope
- $\alpha$  = slope angle
- $\gamma_{water}$  = unit weight or density of water
- $\gamma_{sat}$  = saturated unit weight of clay liner
- z = vertical distance from middle of clay liner to the seasonal high water table

**Figure 10D-24** Failure of compacted liner from uplift forces below clay blanket (Photo credits NRCS, TX)

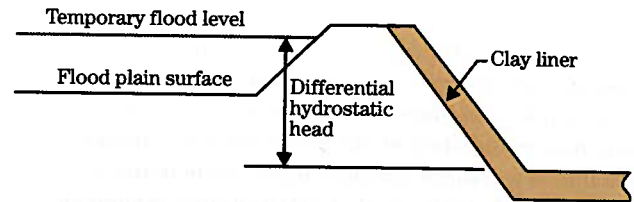




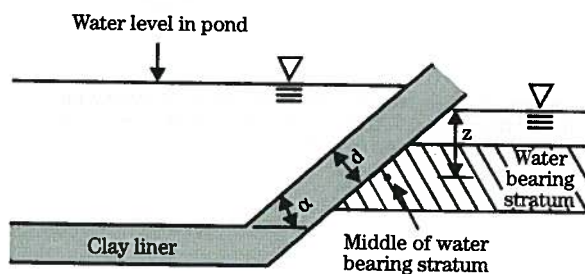
A factor of safety of at least 1.1 should be attained. The safety factor can be increased by using a thicker blanket or providing some means of intercepting the ground water gradient and lowering the potential head behind the blanket. Often, sites where seasonal high water tables are anticipated designs include a perimeter drain to collect the water and prevent this type of damage. Another option is a concrete structure above ground.

Another situation where a clay liner may be damaged from hydrostatic pressure is one where 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 location to avoid a seasonal high water table. Figure 10D-26 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 impoundment 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 and boils, and sloughing of side slopes can occur as shown in figure 10D-26. The photo shows a clay-lined animal waste impoundment where the clay liner was damaged from excessive hydrostatic uplift forces caused by temporary storage of flood waters outside the embankment. The liner must be thick enough to resist predicted buoyant forces if it is possible for the pond to be empty or near empty during a flood. Drains will be ineffective because in a flood, outlets will be submerged.

**Figure 10D-26** Uplift conditions caused by temporary flood stage outside lagoon (Photo credit NRCS, WA)



**Figure 10D-25** Uplift calculations for high water table and clay blanket (from Oakley 1987)



## Perimeter drains for animal waste storage ponds

When a high water table is anticipated and uplift pressures are anticipated, one approach to solving the problem is to install a drain around the pond. The drain may completely encircle the pond if a designer anticipates a general elevated water table in the site vicinity. At other sites with a more sloping ground surface, the perimeter drain may only be installed on the side(s) of the impoundment where the elevated water table is anticipated. Drains may be used both for clay liners and geosynthetic liners.

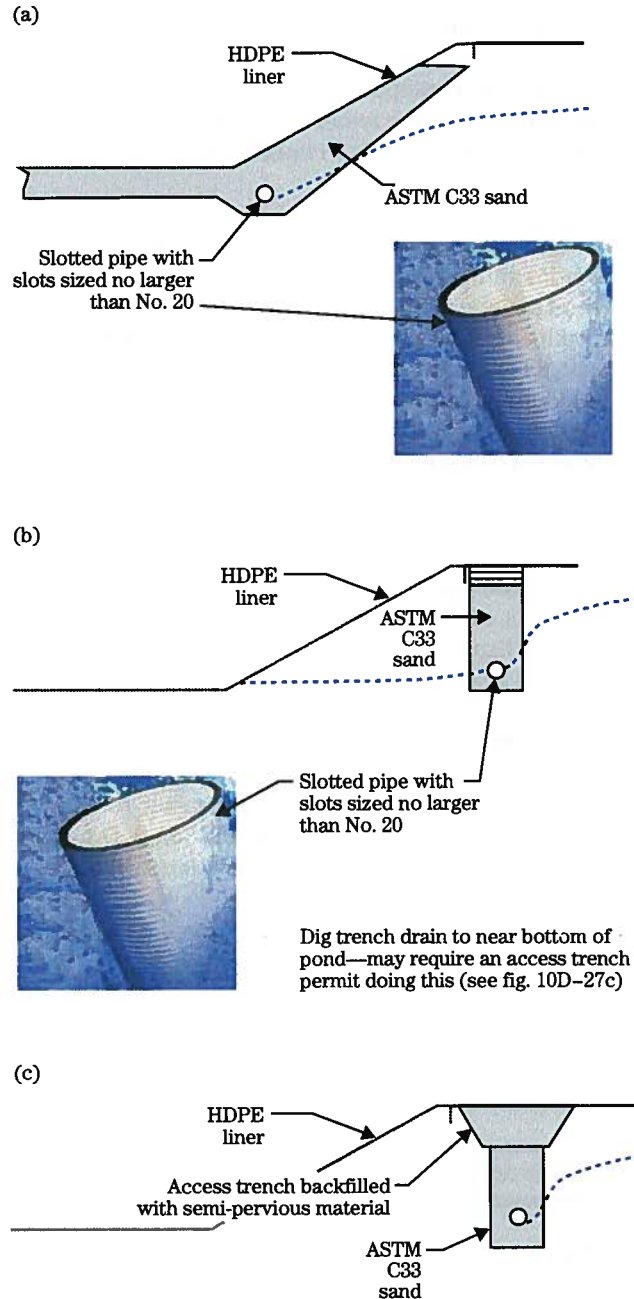
Drains usually are constructed by

- digging a trench to the depth needed to draw down the water table
- placing a perforated or slotted drainage pipe
- surrounding the drain with granular material that is compatible with both the slot size in the pipe and the gradation of the surrounding foundation soils

Pipes with small slots that are compatible with a filter sand like ASTM C-33 are preferred to avoid having to use two filter gradations. If pipes with larger perforations are used, they should be surrounded with gravel to prevent particles from moving into the pipe. Figure 10D-27 (a, b, and c) show typical installations where a single filter and perforated pipe is used. Another approach to installing a drain is to dig a trench, line it with geotextile, and after putting a slotted collector pipe in the trench, filling it with gravel. Figure 10D-28 shows this type of installation.

Several types of drain pipe may be used. One type is a low strength corrugated pipe with slots or perforations surrounded by a filter envelope of granular material. Figure 10D-29 is an example of this type of collector pipe. If a higher strength pipe is required, figure 10D-30 shows another type of pipe that is sometimes used for these types of installations.

**Figure 10D-27** Typical drain installations using single filter with well-screened collector pipe



Illustrated access trench construction to permit installing deeper trench drain. Access trench filled with semi-pervious soil to limit infiltration of surface runoff.



**Figure 10D-28** Perforated collector pipe installed the gravel envelope with trench lined with geotextile



**Figure 10D-30** Corrugated drainage pipe with slots, doubled walled pipes may be specified if higher strengths are needed



**Figure 10D-29** Low-strength perforated drainage tubes





## Soil mechanics testing for documentation

Laboratory soil testing may be required by regulations for design, or a designer may not choose to rely on correlated permeability test values. The NRCS National Soil Mechanics Center Laboratories have the capability to perform the necessary tests. Similar testing is also available at many commercial labs. The

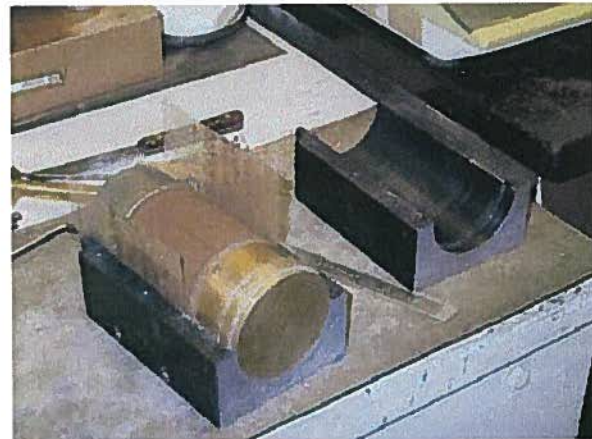
accepted method of permeability testing is by ASTM Standard Test Method D5084, Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. Figure 10D-31 shows the equipment used for performing the test.

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

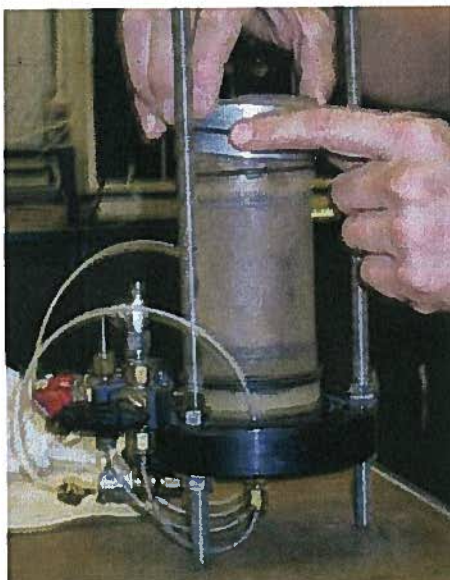
**Figure 10D-31** Equipment used for performing ASTM D5084



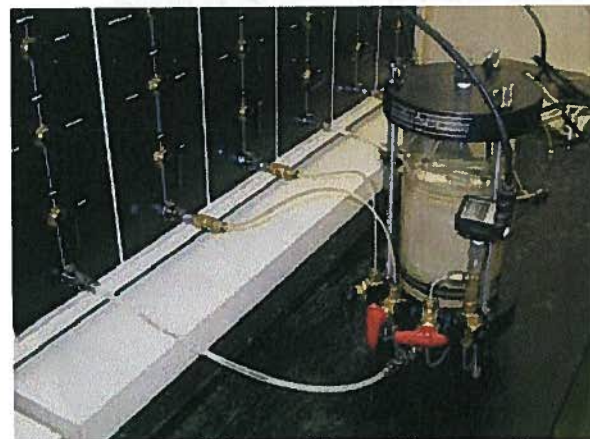
Molding a sample for a flexible wall permeability test



Disassembled mold with compacted specimen



Preparing sample in cell for flexible wall permeability test



Molded sample after disassembling mold

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 <sup>1/</sup> (%)	Sample moist weight (lb)
0-10	5
10-50	20
>50	40

<sup>1/</sup> 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 <sup>1/</sup> (%)	Sample moist weight (lb)
0-10	50
10-50	75
>50	100

<sup>1/</sup> 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.

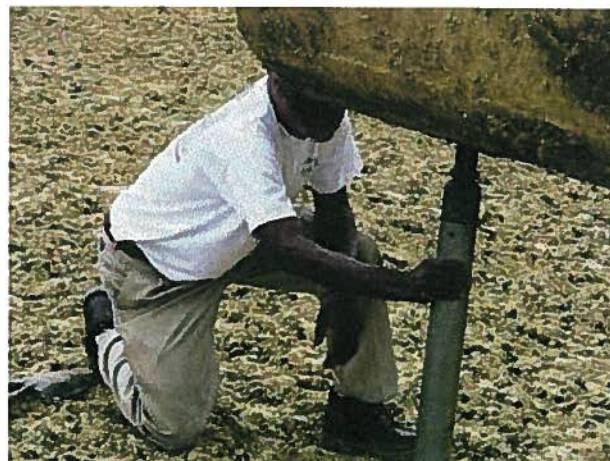
If designs rely on a minimum degree of compaction and water content to achieve stated permeability goals in a clay liner, testing of the clay liner during construction may be advisable to verify that design goals have been achieved. Field density and water content measurements are routinely made using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

## Other methods for documenting liner seepage

Performing density/water content tests during construction is a generally accepted method of documenting that a clay liner has been constructed according to specifications. If the liner is found to meet the requirements of the compaction specifications, the assumption is that the permeability values documented from laboratory testing on samples that were compacted at the specified density and water content will be achieved. In some cases, no additional documentation is required. In other cases, regulations require obtaining samples of the completed liner and performing permeability tests on them. Figure 10D-32 shows one way that a Shelby tube type of sample may be obtained without mobilizing a drilling rig. The Shelby tube used is typically a standard tube with a 3-inch outside diameter and 2 7/8-inch inside diameter. This size sample can be placed directly in a flexible wall permeameter for testing, after extrusion in the laboratory.

Another method for obtaining a sample of a compacted clay liner is with a drive sampler like that shown in figure 10D-33.

**Figure 10D-32** Shelby tube sample being obtained with backhoe bucket used to force tube into clay liner (Photo credit Jody Kraenzel, NRCS, NE)





**Figure 10D-33** Obtaining undisturbed sample of compacted clay liner using thin-walled drive cylinder



In the situation where a storage pond was constructed several years before documentation on quality of construction and permeability was required, studies are sometimes made in an attempt to measure seepage losses directly. One approach that has been used was developed by researchers at Kansas State University. This approach involves installing precise water level monitoring devices and evaporation stations. Seepage losses can be estimated by carefully monitoring the levels in the pond during periods when no waste is introduced into the pond and no rainfall occurs. After estimating the amount of evaporation, and subtracting that from the total decline in the level of the pond during that period, seepage loss can be estimated. Figure 10D-34 shows equipment for measuring evaporation in a pond.



**Figure 10D-34** Equipment used to monitor evaporation at an agriculture waste storage lagoon. Measurements are used in total lagoon seepage evaluations.



## 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. Its effectiveness is not accepted by all designers and cannot be used in the designs of storage ponds by some State and local regulations.
- Soils can be divided into four permeability groups based on their percent fines (percent finer than the No. 200 sieve) and plasticity index (PI). Soils in groups III and IV may be assumed to have a coefficient of permeability of  $1 \times 10^{-6}$  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 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 the low permeability horizons 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.
- Allowable specific discharge values are discussed and guidance is provided on reasonable values to use for design when other regulatory requirements are not specified.
- Flexibility is built into the design process. The depth of the liquid, the permeability, and thick-

ness of the soil liner can be varied to provide an acceptable specific discharge.

- The guidelines provided for design of clay liners in this appendix provide designers with the tools to evaluate the probable unit seepage or specific discharge through a clay liner. The methods presented allow a designer to determine what treatment is required to achieve specific discharge or permeability goals.
- Methods provide designers with the ability to evaluate the effect of changes in a proposed design on the estimated unit seepage rate.
- As additional research becomes available, practice standards and guidance in this document may warrant revision.

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