Chapter 5

Soil Drainage Systems

5.1 Introduction and Background

Natural soil drainage materials are used extensively in waste containment units. The most common uses are:

1. Drainage layer in final cover system to reduce the hydraulic head on the underlying barrier layer and to enhance slope stability by reducing seepage forces in the cover system.
2. Gas collection layer in final cover systems to channel gas to vents for controlled removal of potentially dangerous gases.
3. Leachate collection layer in liner systems to remove leachate for treatment and to remove precipitation from the disposal unit in areas where waste has not yet been placed.
4. Leak detection layer in double liner systems to monitor performance of the primary liner and, if necessary, to serve as a secondary leachate collection layer.
5. Drainage trenches to collect horizontally-flowing fluids, e.g., ground water and gas.

Drainage layers are also used in miscellaneous ways, such as to drain liquids from backfill behind retaining walls or to relieve excess water pressure in critical areas such as the toe of slopes.

5.2 Materials

Soil drainage systems are constructed of materials that have high hydraulic conductivity. High hydraulic conductivity is not only required initially, but the drainage material must also maintain a high hydraulic conductivity over time and resist plugging or clogging. The hydraulic conductivity of drainage materials depends primarily on the grain size of the finest particles present in the soil. An equation that is occasionally used to estimate hydraulic conductivity of granular materials is Hazen's formula:

$$k = (D_{10})^2 \qquad (5.1)$$

where k is the hydraulic conductivity (cm/s) and D_{10} is the equivalent grain diameter (mm) at which 10% of the soil is finer by weight. To determine the value of D_{10}, a plot is made of the grain-size distribution of the soil (measured following ASTM D-422) as shown in Fig. 5.1. The equivalent grain diameter (D_{10}) is determined from the grain size distribution curve as shown in Fig. 5.1.

Experimental data verify that the percentage of fine material in the soil dominates hydraulic conductivity. For example, the data in Table 5.1 illustrate the influence of a small amount of fines upon the hydraulic conductivity of a filter sand. The addition of just a few percent of fine material to a drainage material can reduce the hydraulic conductivity of the drainage material by 100 fold or more.

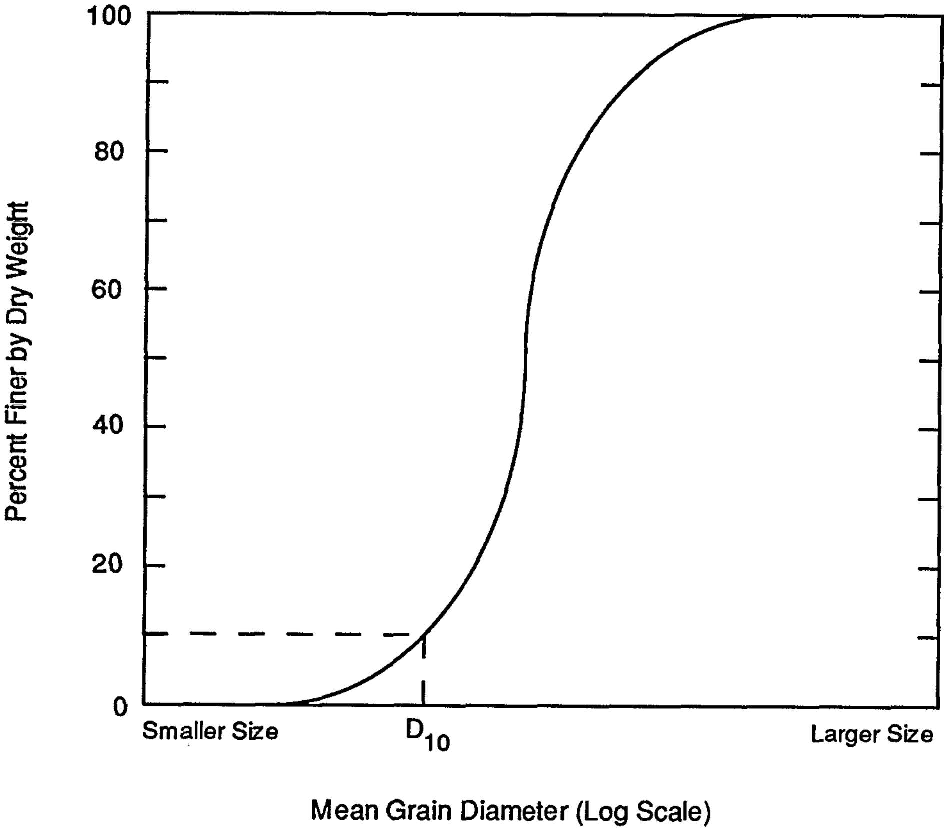

Figure 5.1 - Grain Size Distribution Curve

Construction specifications usually stipulate a minimum hydraulic conductivity for the drainage layer. The value specified varies considerably from project to project but is typically in the range of 0.01 to 1 cm/s. The method used to determine hydraulic conductivity in the laboratory is ASTM D-2434.

Table 5.1 Effect of Fines on Hydraulic Conductivity of a Washed Filter Aggregate (from Cedergren, 1989)

Percent Passing No. 100* Sieve	Hydraulic Conductivity (cm/s)
0	0.03 to 0.11
2	0.004 to 0.04
4	0.0007 to 0.02
6	0.0002 to 0.007
7	0.00007 to 0.001

*Opening size is 0.15 mm.

Drainage materials may also be required to serve as filters. For instance, as shown in Fig. 5.2, a filter layer may be needed to protect a drainage layer from plugging. The filter layer must serve three functions:

1. The filter must prevent passage of significant amounts of soil through the filter, i.e., the filter must retain soil.
2. The filter must have a relatively high hydraulic conductivity, e.g., the filter should be more permeable than the adjacent soil layer.
3. The soil particles within the filter must not migrate significantly into the adjacent drainage layer.

Filter specifications vary somewhat, but the design procedures are similar. The determination of requirements for a filter material proceeds as follows:

1. The grain size distribution curve of the soil to be retained (protected) is determined following procedures outlined in ASTM D-422. The size of the protected soil at which 15% is finer ($D_{15,\text{ soil}}$) and 85% is finer ($D_{85,\text{ soil}}$) is determined.
2. Experience shows that the particles of the protected soil will not significantly penetrate into the filter if the size of the filter at which 15% is finer ($D_{15,\text{ filter}}$) is less than 4 to 5 times D_{85} of the protected soil:

$$D_{15,\text{ filter}} \leq (4 \text{ to } 5)\, D_{85,\text{ soil}} \tag{5.2}$$

3. Experience shows that the hydraulic conductivity of the filter will be significantly greater than that of the protected soil if the following criterion is satisfied:

$$D_{15,\text{ filter}} \geq 4\ D_{15,\text{ soil}} \tag{5.3}$$

4. To ensure that the particles within the filter do not tend to migrate excessively into the drainage layer, the following criterion may be applied:

$$D_{15,\text{ drain}} \leq (4 \text{ to } 5)\ D_{15,\text{ filter}} \tag{5.4}$$

5. Experience shows that the hydraulic conductivity of the drain will be significantly greater than that of the filter if the following criterion is satisfied:

$$D_{15,\text{ drain}} \geq 4\ D_{15,\text{ filter}} \tag{5.5}$$

Filter design is complicated significantly by the presence of biodegradable waste materials, e.g., municipal solid waste, directly on top of the filter. In such circumstances, the usual filter criteria may be modified to satisfy site-specific requirements. Some degree of reduction in hydraulic conductivity of the filter layer may be acceptable, so long as the reduction does not impair the ability of the drainage system to serve its intended function. A laboratory test method to quantify the hydraulic properties of both soil and geotextile filters that are exposed to leachate is ASTM D-1987. However, regardless of specific design criteria, the gradational characteristics of the filter material control the behavior of the filter. CQC/CQA personnel should focus their attention on ensuring that the drainage material and filter material meet the grain-size-distribution requirements set forth in the construction specifications, as well as other specified requirements such as mineralogy of the materials.

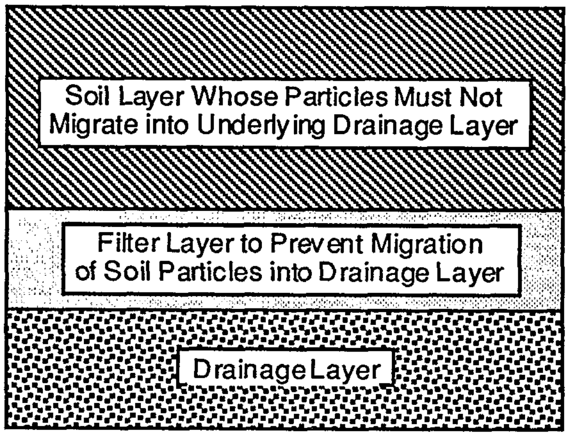

Figure 5.2 - Filter Layer Used to Protect Drainage Layer from Plugging

5.3 Control of Materials

The recommended procedure for verifying the hydraulic conductivity for a proposed drainage material is as follows. Samples of the proposed material should be obtained and shipped to a laboratory for testing. Samples should be compacted in the laboratory to a density that will be representative of the density to be used in the field. Hydraulic conductivity should be measured following procedures in ASTM D-2434 and compared with the required minimum values stated in the construction specifications. If the hydraulic conductivity exceeds the minimum value, the material is tentatively considered to be acceptable. However, it should be realized that the process of excavating and placing the drainage material will cause some degree of crushing of the drainage material and will produce additional fines. Thus, the construction process itself tends to increase the amount of fines in the drainage material and to decrease the hydraulic conductivity of the material. If the drainage material just barely meets the hydraulic conductivity requirements stated in the construction specifications from initial tests, there is a good possibility that the material will fail to meet the required hydraulic conductivity standard after the material has been placed. As a rule of thumb, approximately one-half to one percent of additional fines by weight will be generated every time a drainage material is handled, e.g., one-half to one percent additional fines would be generated when the drainage layer material is excavated and an additional one-half to one percent of fines would be generated when the material is placed. Also, the reproducibility of hydraulic conductivity tests is not well established; a material may just barely meet the hydraulic conductivity standard in one test but fail to meet minimum requirements in another test. Finally, if the drainage materials are found to be suitable prior to placement but unsuitable after placement, an extremely difficult situation arises -- it is virtually impossible to remove and replace the drainage material without risking damage to underlying geosynthetic components, e.g., a geomembrane. Therefore, some margin of safety should be factored into the selection of drainage material.

Because it is extremely difficult to remove and replace a drainage material without damaging an underlying geosynthetic component, testing of the drainage material should occur prior to placement of the material. The CQC personnel should have a high degree of confidence that the drainage material is suitable prior to placement of the material. Because the construction process may alter the characteristics of the drainage material, it is important that CQA tests also be performed on the material after it has been placed and compacted (if it is compacted).

The usual tests involve determination of the grain size distribution of the soil (ASTM D-422) and hydraulic conductivity of the soil (ASTM D-2434). Hydraulic conductivity tests tend to be time consuming and relatively difficult to reproduce precisely; the test apparatus that is employed, the compaction conditions for the drainage material, and other details of testing may significantly influence test results. Grain-size distribution analyses are simpler. Therefore, it is recommended that the CQA testing program emphasize grain-size distribution analyses, with particular attention paid to the amount of fines present in the drainage material, rather than hydraulic conductivity testing. The percent of fines is normally defined as the percent on a dry weight basis passing through a No. 200 sieve (openings of 0.075 mm). Again, it is emphasized that close testing and inspection of the borrow source or the supplier prior to placement of the material is critical, particularly if the drainage material is underlain by a geosynthetic material.

The recommended tests and frequency of testing are shown in Table 5.2. The same principles for sampling strategies discussed in Chapter 2 may be applied to location of tests or location of samples for drainage layer materials. Also, occasional failing tests may be allowed, but it is recommended that no more than 5% of the CQA tests be allowed to deviate from specifications, and the deviations should be relatively minor, i.e., no more than about 2% fines beyond the maximum value allowed and no less than about one-fifth the minimum allowable hydraulic conductivity.

Table 5.2 - Recommended Tests and Testing Frequencies for Drainage Material

Location of Sample	Type of Test	Minimum Frequency
Potential Borrow Source	Grain Size (ASTM D-422)	1 per 2,000 m^3
	Hydraulic Conductivity (ASTM D-2434)	1 per 2,000 m^3
	Carbonate Content* (ASTM D-4373)	1 per 2,000 m^3
On Site; After Placement and Compaction	Grain Size (ASTM D-422)	1 per Hectare for Drainage Layers; 1 per 500 m^3 for Other Uses
	Hydraulic Conductivity (ASTM D-2434)	1 per 3 Hectares for Drainage Layers; 1 per 1,500 m^3 for Other Uses
	Carbonate Content* (ASTM D-4373)	1 per 2,000 m^3

*The frequency of carbonate content testing should be greatly reduced to 1 per 20,000 m^3 for those drainage materials that obviously do not and cannot contain significant carbonates (e.g., crushed basalt).

5.4 Location of Borrow Sources

The construction specifications usually establish criteria that must be met by the drainage material. Earthwork contractors are normally given latitude in locating a suitable source of material that meets construction specifications. On occasion the materials may be available on site or from a nearby piece of property, but most frequently the materials are supplied by a commercial materials company. If the materials are supplied by an existing materials processor, stockpiles of materials are usually readily available for testing and no geotechnical investigations are required, other than to test the proposed borrowed material.

5.5 Processing of Materials

Materials may be processed in several ways. Oversized stones or rocks are typically removed by sieving. Fine material may also be removed by sieving. Washing the fines out of a sand or gravel can be particularly effective in removing silt and clay sized particles from granular material. For drainage layer materials that are supplied from a commercial processing facility, the facility owner is usually experienced in processing the material to remove fines.

For the CQA inspector the main processing issues are removal of oversized material, removal of angular material (if required to minimize potential to puncture a geomembrane), and assurance that excessive fines will not be present in the material.

On occasion the amount of limestone, dolostone, dolomite, calcite, or other carbonates in the drainage material may be an issue. Carbonate materials are slightly soluble in water. If the drainage material contains excessive carbonate, the carbonate may dissolve at one location and precipitate at another, plugging the material. CQA inspectors should also be cognizant of the need to make sure that carbonate components are not present in excessive amounts. If the specifications place a limit on carbonate content, tests should be performed to confirm compliance (Table 5.2).

5.6 Placement

Drainage materials may be placed in layers (e.g., as leachate collection layers) or they may be placed in drainage trenches (e.g., to provide drainage near the toe of a slope). Placement considerations differ depending on the application.

5.6.1 Drainage Layers

Granular drainage materials are usually hauled to the placement area in dump trucks, loosely dumped from the truck, and spread with bulldozers. The contractor should dump and spread the drainage material in a manner that minimizes generation of fine material. For instance, light-contact-pressure dozers can be used to spread the drainage material and minimize the stress on the granular material. Granular materials placed on top of geosynthetic components on side slopes should be placed from the bottom of the slope up.

When granular drainage material is placed on a previously-placed geomembrane or geotextile and spread with a dozer, the sand or gravel should be lifted and tumbled forward so as to minimize shear forces on the underlying geosynthetic. The dozer should not be allowed to "crowd" the blade into the granular material and drag it over the surface of the underlying geosynthetic material.

Granular materials are often placed with a backhoe in small, isolated areas such as sumps. Some drainage materials may even be placed by hand, e.g., in sumps and around drainage pipes.

CQA personnel should position themselves in front of the working face of the placement operation to be able to observe the materials as they are spread and to ensure that there is no puncture of underlying materials. CQA personnel should observe placement of drainage layers to ensure that fine-grained soil is not accidentally mixed with drainage material.

5.6.2 Drainage Trenches

Drainage materials are often placed in trenches to provide for subsurface drainage of water. A typical trench configuration is shown in Fig. 5.3. Often, a perforated pipe will be placed in the bottom of the trench. Geotextile filters are often required along the side walls to prevent migration of fine particles into the drainage material. CQA personnel should carefully review the plans and specifications to ensure that the drainage and filter components have been properly located in the trench prior to backfill.

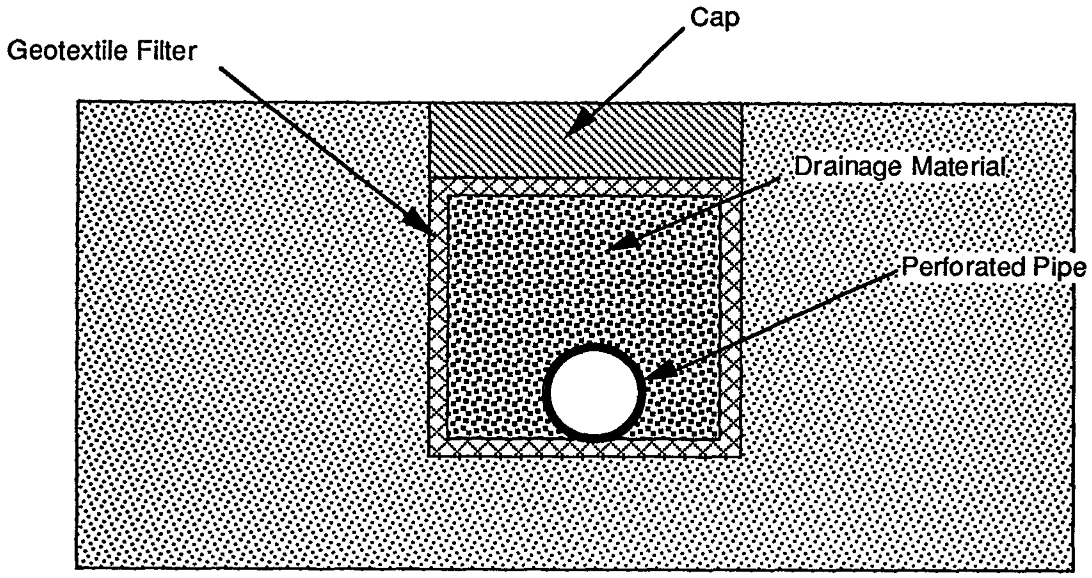

Figure 5.3 - Typical Design of a Drainage Trench

CQC/CQA personnel should be aware of all applicable safety requirements for inspection of trenches. Unsupported trenches can pose a hazard to personnel working in the trench or inspecting the trench. For trenches that are supported by shoring, CQA personnel should review with the contractor the plan for pulling the shoring in terms of the timing for placement of materials and ensure that the procedures are in accord with the specifications for the project.

Granular backfill is usually placed in a trench by a backhoe. For narrow trenches, a "tremie" is commonly used to direct the material into the trench without allowing the material to come into contact with soil on the sidewalls of the trench. Sometimes drainage materials are placed by hand for very small trenches.

A special type of trench involves support of the trench wall with a biodegradable ("biopolymer") slurry. The trench is excavated into soil using a biodegradable, viscous fluid to maintain the stability of the trench. The backfill is placed into the fluid-filled trench. An agent is introduced to promote degradation of the viscous drilling fluid, which quickly loses much of its viscosity and allows the granular backfill to attain a high hydraulic conductivity without any plugging effect from the slurry. This technology allows construction of deep, continuous drainage trenches but is used much more often for remediation of contaminated sites than in new waste containment facilities. Further details are given by Day (1990).

5.7 Compaction

Many construction specifications stipulate a minimum percentage compaction for granular drainage layers. There is rarely a need to compact drainage materials. However, on occasion, there may be a need to compact a drainage material for one of the following reasons:

1. If a settlement-sensitive structure is to be placed on top of the drainage layer, the drainage layer may need to be compacted to minimize settlement.
2. If dynamic loads might cause loose drainage material to liquefy or settle excessively, the material may need to be compacted.
3. If the drainage material must have exceptionally high strength, the material may need to be compacted.

Only in rare instances will the problems listed above be significant. Settlement-sensitive structures are rarely built on top of liner or cover systems. Liquefaction is rarely an issue because the hydraulic conductivity of the drainage material is normally sufficiently large to preclude the possibility of liquefaction. Strength is rarely a problem with granular materials. Reasons not to compact the drainage layer are as follows:

1. Compacting the drainage material increases the amount of fines in the drainage material, which decreases hydraulic conductivity.
2. Compacting the drainage layer reduces the porosity of the material, which decreases hydraulic conductivity.
3. Dynamic compaction stresses may damage underlying geosynthetics.

Unless there is a sound reason why the drainage material should be compacted, it is recommended that the drainage material not be compacted. The main goal of the drainage layer is to remove liquids, and this can only be accomplished if the drainage layer has high hydraulic conductivity. The uncompacted drainage layer may be slightly compressible, but the amount of compression is expected to be small.

There is a potential problem with drainage layer materials placed on side slopes. In some situations the friction between the drainage layer and underlying geosynthetic component may not be adequate to maintain stability of the side slope. CQA personnel should assume that the designer has analyzed slope stability and designed stable slide slopes for assumed materials and conditions. However, CQA personnel should be vigilant for evidence of slippage at the interface between the drainage layer and an underlying geosynthetic component. If problems are noted, the design engineer should be notified immediately.

5.8 Protection

The main protection required for the drainage layer is to ensure that large pieces of waste material do not penetrate excessively into the layer and that fines do not contaminate the layer. Many designs call for placement of protective soil or select waste on top of the leachate collection layer. As shown in Fig. 5.4, CQA personnel should stand near the working face of the first lift of solid waste placed on top of a leachate collection layer in a solid waste landfill to observe placement of select material.

Wind-borne fines may contaminate drainage materials. Soil erosion from adjacent slopes may also lead to accumulation of fines in the drainage material. The CQA personnel cannot complete their job until the drainage material is fully covered and protected.

Residual fines may be washed by rain from other soils, or the drainage material itself, during rain storms and accumulate in low areas. The accumulation of fines in sumps or other low points can reduce the effectiveness of the drainage system. CQC/CQA personnel should be aware of this potential problem and watch for (1) areas where fines may be washed into the drainage material; and (2) evidence of lack of free drainage in low-lying areas (e.g., development of ponds of water in the drainage material in low-lying areas). If excessive fines are washed into a portion of the drainage material, the design engineer should be contacted for further evaluation prior to covering the drainage material by the next successive layer in the system.

Figure 5.4 -- CQC and CQA Personnel Observing Placement of Select Waste on Drainage Layer.

5.9 References

ASTM D-422, "Particle Size Analysis of Soils"

ASTM D-1987, "Biological Clogging of Geotextile or Soil/Geotextile Filters"

ASTM D-2434, "Permeability of Granular Soils"

ASTM D-4373, "Calcium Carbonate Content of Soils"

Cedergren, H.R. (1989), *Seepage, Drainage, and Flow Nets*, Third Edition, John Wiley & Sons, New York, 465 p.

Day, S. R. (1990), "Excavation/Interception Trenches by the Bio-Polymer Slurry Drainage Trench Technique," *Superfund '90*, Hazardous Materials Control Research Institute, Silver Spring, Maryland, pp. 382-385.