26

Geo-Environment

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26.1 Introduction

The objective of this chapter is to present the main applications of geotechnical engineering to environmental projects. There are numerous examples of these applications, among which the most frequent are waste disposal projects, environmental compliance projects, and environmental remediation projects.

Although some projects could be classified under more than one category, in this introduction they are separated depending on whether the project is (1) to be designed prior to the disposal of waste; (2) the objective of the project is to control **releases** to the environment caused by current activities or to bring a facility into compliance with current environmental or health and safety regulations; or (3) the objective is to remediate a site impacted by previous releases and/or control releases from contaminants or wastes accumulated at a site. Although there is not uniformity in these definitions, generally the term *environmental compliance* is applied to active facilities, whereas *environmental remediation* is applied to closed facilities.

The main objective of the three categories of projects mentioned above is to reduce or minimize impacts to the environment. Releases that impact the environment may occur through the disposal or spreading of **solid wastes** or **liquid wastes**, the infiltration or runoff of liquids that have been in contact with wastes, or through gaseous emissions. These releases may, in turn, impact different media. They may carry contaminants into soils located in upland areas or into sediments within water bodies, transport liquids or dissolved contaminants through groundwater or surface water bodies, or be released to the atmosphere.

The geo-environmental structures used to reduce or minimize the propagation of contaminants through the different media are called containment systems. The most commonly used containment systems are **liner** systems, cover systems (or caps), and slurry wall cut-offs. The use of liner systems is generally limited to new projects or expansions, while cover systems and slurry walls are used with all categories of projects.

This chapter presents a brief description of the main categories of environmental projects mentioned above, followed by a detailed discussion of liner and cover systems, including materials used for their construction and some construction-related aspects.

Waste Disposal Projects

As indicated above, the first category of environmental projects comprises those projects designed and constructed to contain waste materials prior to the disposal of waste. This includes projects such as landfills, **lagoons**, and tailings impoundments. Although tailings impoundments are basically landfills, their design and operation, requiring simultaneous management of liquids and solids, differs substantially from typical landfills, in which mostly solids are managed, and therefore it is justified to consider them as a different type of project.

A brief discussion of landfill projects is presented below as an introduction to the use of containment systems in environmental projects. For brevity, a discussion of tailings impoundments and lagoons is omitted. However, the reader should keep in mind that several of the elements of landfill projects have similar application for tailings impoundments and lagoons.

Modern landfills are complex structures that include a number of systems to prevent undue releases to the environment. The main systems are:

- Bottom liner system
- Final cover system
- Surface water management system
- **Leachate** management system (leachate collection, removal, and disposal systems)
- Gas management system
- Environmental monitoring system

Although all these systems are important to prevent undue releases to the environment, only the bottom liner and the final cover systems will be discussed, since the other systems are beyond the scope of this chapter. The function of the liner system is to contain leachate and prevent it from migrating downward into the subsoil or groundwater. The function of the final cover is to control infiltration of precipitation into the waste, to prevent contact of runoff with the waste, to prevent the displacement or **washout** of wastes to surrounding areas, to reduce the potential for disease **vectors** (birds, insects, rodents, etc.), and to control the emission of gases.

Landfills may be classified in accordance with several criteria. The most common criteria used to classify landfills are type of waste, type of liner system, and geometrical configuration. Based on current federal regulations, landfills are classified with respect to the type of waste as **municipal solid waste** (MSW), **hazardous waste**, and other types of solid waste. Federal regulations regarding these three types of landfills are published in Sections 258, 264, and 257, respectively, of the Code of Federal Regulations. State regulations are, however, frequently more stringent than federal regulations. State regulations frequently include specific regulations for landfills where other types of waste will be disposed, such as **industrial waste**, **construction demolition debris**, and residual waste.

With respect to the liner system, landfills are classified as single or double lined. Liner systems comprising only one (primary) liner are called single-liner systems. Liner systems comprising a primary and a secondary liner, with an intermediate leachate detection system, are called double liner systems. Each of the liners (primary or secondary) may consist of only one layer [clay, geomembrane, or geosynthetic clay liner (GCL)] or adjacent layers of two of these materials, in which case it is called a composite liner. A detailed discussion of liner systems is presented later in this chapter.

The geometrical configuration of a landfill is the result of a number of factors that have to be considered during the design. It is generally intended to design the subgrade excavation as deep as possible, so that airspace is maximized and soils are made available for daily, intermediate, and final covers, structural fill, soil liners, perimeter and intercell berms, sedimentation basin berms, and access roads. However, the footprint shape and extent, cell layout, excavation depth, and subbase grading are strongly influenced by the following factors:

- Depth to the water table or uppermost aquifer. Some regulations require a minimum separation from the water table. Even if regulations do not require separation from the water table, excavation dewatering has a significant cost impact.
- Depth to bedrock. The cost of hard-rock excavation negatively impacts the economic feasibility of a project. Additionally, excavated rock generally has little use in landfill projects.

- Stability of the foundation. Weak foundation soils, as well as areas previously mined or susceptible to sinkhole development, may cause instability problems.
- Site topography and stability of natural and cut slopes. In flat areas only fill embankments and cut slopes need to be considered, whereas excavations close to natural slopes may affect their stability and need to be considered in selecting the landfill footprint.
- Stability of cut slopes. The stability of cut slopes is a function of their height, inclination, groundwater conditions, and the strength and unit weight of the *in situ* soils. The inclination and height of the cut slopes affects the landfill airspace and the volume of soils to be excavated.
- Soils balance. The soils balance refers to the types and volumes of soils available and needed. An adequate soils balance allows a sufficient volume of soils to be available from on-site excavations and, at the same time, avoids excessive excavation that would have to be stockpiled on-site or disposed off-site.
- Permeability of natural soils. In some cases a natural clay liner may be acceptable, which would eliminate the need for low-permeability borrow for an engineered liner.
- Required airspace and available area. A minimum airspace may be required to make the landfill project economically feasible.
- Waste stream. The waste rate is directly related to the life of each cell. Normally cells are dimensioned so that they do not remain empty for an extended period of time.
- Filling sequence. One of the design goals is to avoid excessive stockpiling of excavated soils and to minimize leachate production by placing the final cover as soon as possible.
- Grading of the landfill floor. A minimum slope is required for the leachate collection system.

Finally, from the point of view of geometrical configuration, the most common landfill types are:

- Area fill. Landfilling progresses with little or no excavation (Fig. 26.1). Normally used in relatively flat areas with shallow water table.
- Above-ground and below-ground fill. The landfill consists of a two-dimensional arrangement of large cells that are excavated one at a time. Once two adjacent cells are filled, the area between them is also filled (Fig. 26.2). Normally used in relatively flat areas without a shallow water table.
- Valley fill. The area to be filled is located between natural slopes (Fig. 26.3). It may include some below-ground excavation.
- Trench fill. This method is similar to the above-ground and below-ground configuration, except that the cells are narrow and parallel (Fig. 26.4). It is generally used only for small waste streams.

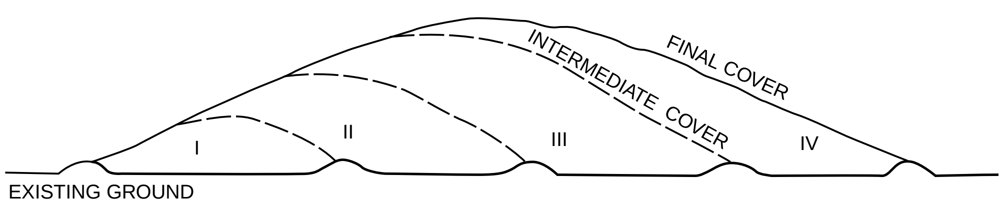

FIGURE 26.1 Area fill.

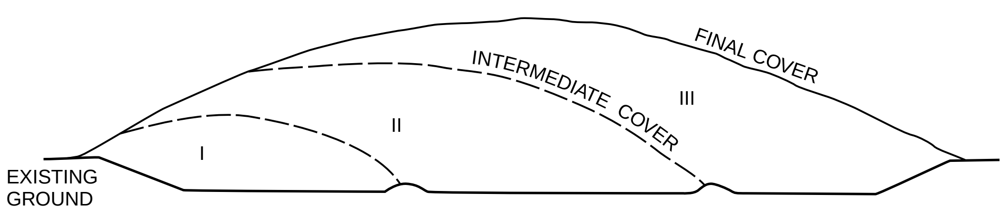

FIGURE 26.2 Above-ground and below-ground fill.

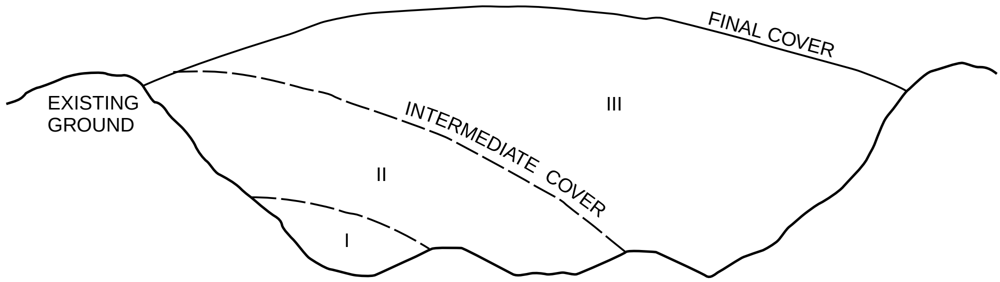

FIGURE 26.3 Valley fill.

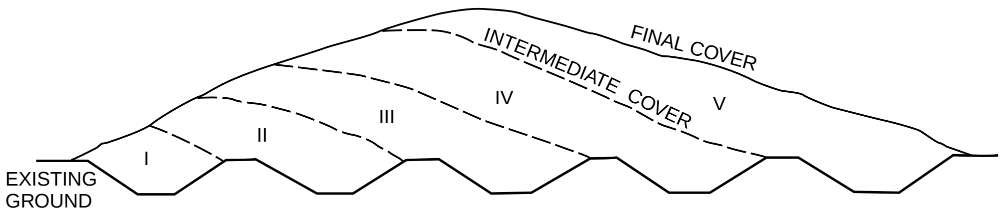

FIGURE 26.4 Trench fill.

Environmental Compliance Projects

The second category comprises a very broad range of projects, in which the aim is to bring a facility into compliance with current regulations (including health and safety) and/or to control releases to the environment caused from current site activities. As mentioned above, these releases may occur through solid, liquid, or gaseous discharges, and may affect soils, sediments, water bodies, or the atmosphere. The type of facility involved may be of any kind: landfill, tailings impoundment, lagoon, or any industrial facility.

The actions for controlling releases from active facilities are multiple and can be classified into three major groups:

- Modifications to the operations or processes in the facility itself, with the objective of avoiding or reducing the release of contaminants
- Treatment of discharges, so that contaminants are removed before the discharges take place
- Containment of contaminants (as discussed previously, the main containment systems are liner systems, cover systems, and slurry wall cut-offs)

The first two groups of actions listed above are beyond the scope of this chapter. Containment systems are discussed later in this chapter.

Environmental Remediation Projects

This category comprises projects in which the aim is to control releases to the environment from wastes or contaminants accumulated at a site and/or to remediate areas whose environmental functions have been impaired by previous site activities. As discussed previously, this category of projects generally applies to sites where activities have ceased. As in the case of environmental compliance projects, the types of activities that took place at the site can be of any kind.

The actions used to control releases from closed facilities can be classified into four major groups:

- Removal of the wastes or contaminated materials, and disposal at an appropriate facility
- Fixation or removal of the contaminants in place, so that releases are prevented

- Interception and treatment of contaminated releases
- Isolation of the wastes or contaminated materials by means of containment systems, so that releases are prevented

Of these four groups, only the use of containment systems is within the scope of this chapter and is discussed next.

26.2 Geo-Environmental Containment Systems

Liners

Liner systems are containment elements constructed under the waste to control infiltration of contaminated liquids into the subsoil or groundwater. The contaminated liquid, or leachate, may be part of the waste itself or may originate from water that has infiltrated into the waste.

Liner systems consist of multiple layers which fulfill specific functions. The description presented below refers specifically to landfill liner systems. However, the main characteristics of liner systems are similar for other applications. Landfill liner systems may consist, from top to bottom, of the following functional layers:

- *Protective layer.* This is a layer of soil, or other appropriate material, that separates the **refuse** from the rest of the liner to prevent damage from large objects.
- *Leachate collection layer.* This is a high-permeability layer, whose function is to collect leachate from the refuse and to convey it to sumps from where it is removed. Frequently the functions of the protective layer and the leachate collection layer are integrated in one single layer of coarse granular soil.
- *Primary liner.* This is a low-permeability layer (or layers of two different low-permeability materials in direct contact with each other). Its function is to control the movement of leachate into the subsoil.
- *Secondary leachate collection layer, or leakage detection layer.* This is a high-permeability (or high-transmissivity, if geosynthetic) layer designed to detect and collect any leachate seeping through the primary liner. This layer is used only in conjunction with a secondary liner.
- *Secondary liner.* This is a second (or backup) low-permeability layer (or layers of two different low-permeability materials in direct contact with each other). Not all liner systems include a secondary liner.
- *Drainage layer.* In cases where the liner system is close or below the water table, a high-permeability (or high-transmissivity, if geosynthetic) blanket drainage layer is generally placed under the liner system to control migration of moisture from the foundation to the liner system.
- *Subbase.* This layer is generally of intermediate permeability. Its function is to separate the liner system from the natural subgrade or structural fill.

These layers are normally separated by geotextiles to prevent migration of particles between layers, or to provide cushioning or protection of geomembranes.

As indicated above, liner systems may have a primary liner only or may include primary and secondary liners. In the first case it is called a *single-liner* system, and if it has a primary and a secondary liner it is called a *double-liner* system. Further, each of the liners (primary or secondary) may consist of one layer only (low-permeability soil, geomembrane, or GCL) or adjacent layers of two of these materials, in which case it is called a *composite* liner. There are multiple combinations of these names, some of which are given below as examples (obviously there are many more combinations):

- Single synthetic liner: primary liner only, consisting of a geomembrane.
- Single soil liner: primary liner only, consisting of a low-permeability soil layer.

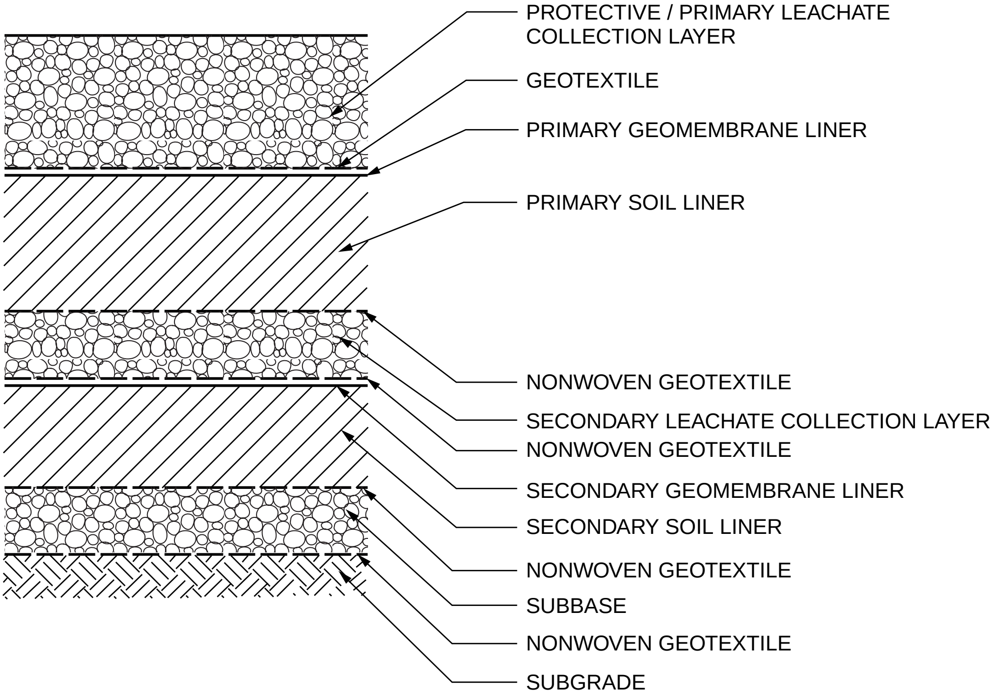

FIGURE 26.5 Double composite liner system.

- Double synthetic liner: primary and secondary liners, each consisting of a geomembrane, separated by a secondary leachate collection layer.
- Single composite liner: primary liner only, consisting of a geomembrane in direct contact with a low-permeability soil layer. (This is the design standard specified in Subtitle D regulations of the Resource Conservation and Recovery Act for **municipal solid waste landfill units**).
- Double composite liner: primary and secondary liners, each consisting of a geomembrane in direct contact with a low-permeability soil layer, separated by a secondary leachate collection layer (see Fig. 26.5).

Low-Permeability Covers

A low-permeability cover is a containment system constructed on top of the waste, primarily to control the infiltration of precipitation. Cover systems control infiltration in two ways: (1) by providing a low-permeability barrier and (2) by promoting runoff with adequate grading of the final surface. Other functions of cover systems are to prevent contact of runoff with waste, to prevent spreading or washout of wastes, to reduce disease vectors, and to control the emission of gases.

Cover systems also consist of multiple layers with specific functions related to the management of surface water. Of the precipitation that falls on a cover, part becomes surface water runoff, a portion infiltrates into the cover, and the remainder is lost through evapotranspiration. A low-permeability cover may include, from top to bottom, the following functional layers (see Fig. 26.6):

- *Erosion (vegetative) layer.* This is a layer of soil capable of supporting vegetation (typically grass) and with good resistance to erosion due to surface water runoff.
- *Infiltration layer.* The functions of this layer, also frequently called **cover material**, are to protect the barrier layer from frost penetration and to separate the precipitation that does not evaporate into runoff and infiltration. Each of these two components of the flow has to be controlled

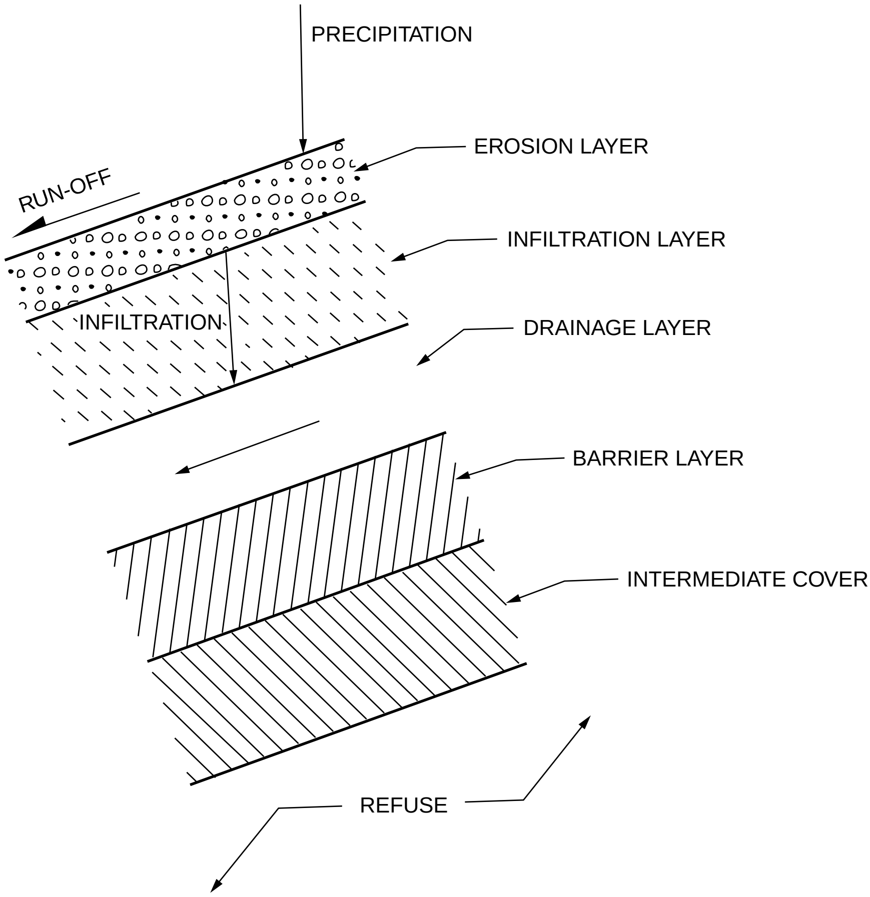

FIGURE 26.6 Cover functional layers.

separately: the runoff through adequate erosion resistance of the erosion layer and the infiltration through adequate hydraulic capacity of the underlying drainage layer.

- *Drainage layer.* This is a permeable layer whose function is to convey the water that infiltrates into the cover system. A cover without a drainage layer is susceptible to damage by pop-outs.
- *Barrier layer.* This is a low-permeability layer (or layers of two different low-permeability materials in direct contact with each other) whose function is to control infiltration into the waste.

The erosion and the infiltration layers are normally constructed of soils, since they must support vegetation and provide frost protection. The drainage layer can be constructed of a permeable soil, a geonet, or a geocomposite. The barrier layer can be constructed of a low-permeability soil, a geomembrane, a GCL, or adjacent layers of two of these materials, in which case it is called a *composite* barrier layer. Some of these layers are also generally separated by geotextiles.

Slurry Walls

Slurry walls are a type of cut-off wall whose function in environmental projects is to control the horizontal movement of contaminated liquids. The single most important characteristic of slurry walls is that the stability of the trench walls during excavation is maintained without any bracing or shoring by keeping the trench filled with a slurry.

During excavation, stability of the trench walls is achieved by maintaining a pressure differential between the slurry inside the trench and the active soil and groundwater pressures acting from outside of the trench. In permeable soils there is initially some loss of slurry, due to the infiltration of slurry from the trench into the surrounding soils. After a short period of time, a low-permeability crust, called *cake*, forms on the trench walls; it provides a hydraulic barrier between the slurry and the groundwater. If the length of trench that is open at any given time is short relative to the height of the trench, the stability is improved by arching effect.

After some length of trench has been excavated, the slurry is displaced and replaced by a permanent backfill mix, consisting either of a soil–bentonite admixture or a bentonite–cement admixture. The backfill mix needs to have low permeability, but at the same time adequate shear strength and low compressibility. The low permeability is achieved by incorporating bentonite into the backfill mix, and the shear strength and low compressibility by including some granular soil or cement as part of the backfill mix.

The most important aspects related to the design and construction of slurry walls are:

- *Keying of the wall bottom*. The intent of slurry walls is to control the lateral flow of liquids. In order to achieve this objective, it is necessary to have the bottom of the trench keyed into a low-permeability stratum, so that flow under the slurry wall is not significant. Therefore, continuity of the low-permeability stratum requires careful consideration.
- *Hydrogeologic effects*. Slurry walls restrict the horizontal flow of groundwater. The effects of introducing this containment system in the hydrogeologic regime, such as mounding upgradient of the wall and drawdown downgradient of the wall, need to be evaluated by means of groundwater modeling.
- *Stability of the trench during excavation*. As indicated above, achieving stability of the trench walls during excavation requires a slurry pressure inside the trench that exceeds the active soil and groundwater pressures acting outside the trench. Calculation of the active soil pressure acting outside the trench must include the effects of adjacent slopes, surcharges, and any other effects that would increase the active soil pressure. Similarly, the groundwater pressure must take into account the effects of upward gradient, confined aquifers, horizontal flow, and any other characteristic of the hydrogeological regime that would affect groundwater pressures.
- *Backfill mix composition*. The backfill mix requires low permeability, adequate shear strength, and low compressibility. Ideally, this is achieved by selecting a backfill mix consisting of granular soil, cohesive soil, and bentonite. The granular soil provides shear strength and reduces compressibility, whereas the cohesive soil reduces the amount of bentonite required to achieve low permeability.

26.3 Liners and Covers

Although the functions of liners and covers are quite different, they use similar materials and are subjected to similar construction considerations. Therefore, for simplicity, the materials used for liners and covers are presented together in this section.

Materials used for the construction of liners and covers can be classified with respect to their origin and function. With respect to their origin they are classified into two major groups: natural soils and geosynthetic materials. With respect to their function the classification is more complex and includes the following:

- *Barrier layers*. These are low-permeability layers of natural soils (clay, soil–bentonite admixtures) or geosynthetic materials (geomembranes, GCLs).
- *Drainage layers*. These are high-permeability (if soil) or high-transmissivity (if geosynthetic) layers. In the first case they consist of granular soils and in the latter of geonets or geocomposites.
- *Fill*. The uses of fill include applications such as grading, intercell berms, perimeter berms, and sedimentation basin berms. Obviously this category is limited to natural soils.
- *Vegetative layer*. Vegetative layers are used as the uppermost layer of final covers, or as erosion protection for permanent or temporary slopes. This category is also limited to natural soils.

- *Filtration/protection/cushion layers*. Liners and covers consist of functional layers of soils of very different gradations, or geosynthetic materials that require special protection to prevent damage during installation or operation. Separation and protection are generally provided by geotextiles placed between functional layers. Geotextiles are placed as filters between soil layers of different gradations to prevent migration of soil particles, as cushion below geomembranes to be installed on granular soils, or as protection on top of geomembranes placed below granular soils.
- *Tensile reinforcement*. In cases where large deformations can be expected in liners or covers, geogrids or geotextiles are used as tensile reinforcement to avoid excessive tensile strains in other elements of the liner or cover system. Additionally, sliding is a potential failure mode in steep cover slopes. In this case geogrids or geotextiles are installed embedded within the layer susceptible to sliding to provide a stabilizing tensile force.

Soils

Barrier Layers

Barrier layers constructed of natural soils may consist of clay or a soil–bentonite admixture. In the case of admixtures, the required bentonite content is selected based on laboratory permeability tests performed with different bentonite percentages.

The typical requirement of most regulations for barrier layers is to have a permeability not exceeding 10^{-7} cm/s. However, since most regulations do not specify under what conditions this value is to be determined, the project specifications must address those conditions. The main factors that influence the permeability of a given soil or soil–bentonite admixture are discussed below:

- *Compaction dry density*. All other factors being constant, the higher the compaction dry density of a soil, the lower its permeability. However, at the same compaction dry density, the permeability also varies as a function of the compaction moisture content and the compaction procedure. The compaction dry density is normally specified as a percentage of the standard or modified Proctor test maximum dry density.
- *Compaction moisture content*. All other factors maintained constant, the permeability of a given soil increases with increasing compaction moisture content. It should be noted, however, that as the moisture content approaches saturation, it becomes more difficult to achieve a target dry density, and other properties of the compacted soil, such as compressibility or shear strength, may become critical.
- *Compaction procedure*. It has been observed that specimens compacted to identical dry densities and moisture contents may exhibit different permeabilities if compacted following different procedures. Therefore, if laboratory test results are close to the required permeability, the compaction procedure used for preparation of laboratory specimens should be similar to the field compaction procedures.
- *Consolidation pressure*. In geo-environmental applications, barrier layers may be subjected to high permanent loads while in service, as is the case in landfill liner systems. In these cases there is an increase in dry density due to consolidation under the service loads. On the other hand, permanent loads are minimal on cover systems and an increase in dry density with time should not be expected. Therefore, permeability tests should be performed using a consolidation pressure consistent with the expected loads.

The combination of compaction dry densities and moisture contents that yields a permeability not exceeding a specified value can be determined by means of a permeability window. A permeability window is constructed by performing permeability tests on a series of specimens compacted at different dry densities and moisture contents, covering the ranges of dry density and moisture content of interest. The specimens should be prepared using a compaction procedure consistent with the field procedure (generally Proctor compaction) and the tests should be performed at a consolidation pressure similar to those to be produced by the expected loads.

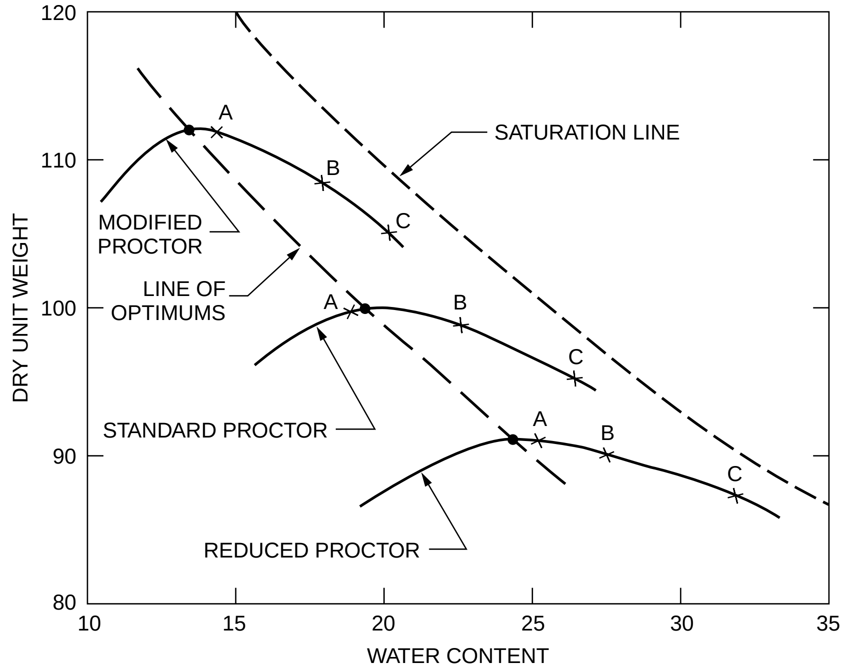

FIGURE 26.7 Dry density–moisture graph.

A practical way of determining a permeability window is described below:

- A large sample of the soil, sufficient to perform three Proctor tests and to prepare nine permeability specimens, should be carefully homogenized, so that differences due to individual specimens are avoided.
- Specific gravity of the soil is determined and the saturation line is plotted in a dry density–moisture graph (see Fig. 26.7).
- Three Proctor tests are performed (modified, standard, and reduced) and plotted in the dry density–moisture graph (Fig. 26.7). The reduced Proctor is a test performed with the same hammer as the standard Proctor, but using a reduced number of blows per layer. Assuming a four-inch mold is used, generally the reduced Proctor is performed using 10 or 15 blows per layer.
- For each of the three Proctor tests, the maximum density and the optimum moisture content are determined, and a line of optimums connecting the three curves is drawn (Fig. 26.7).
- For each of the Proctor curves, three moisture contents are selected corresponding to points on the Proctor curve. The moisture contents typically range from the optimum moisture content to about 95% saturation (points *A*, *B*, and *C* in Fig. 26.7).
- Specimens for permeability testing are prepared at each of the three moisture contents selected above, compacted with the same energy and procedure of the Proctor curve used to select the moisture contents.
- The same procedure is followed for the other two Proctor curves, thus obtaining a total of nine permeability specimens.
- Flexible wall permeability tests are performed on the nine specimens, using a consolidation pressure consistent with the expected loads. Typically the consolidation pressure is selected equal to K_0 times the vertical stress.
- The results of the permeability tests are plotted on the dry density–moisture graph and isopermeability lines are drawn by interpolating between the nine test points (Fig. 26.8). If needed, additional test points may be selected to improve accuracy or to verify questionable points.

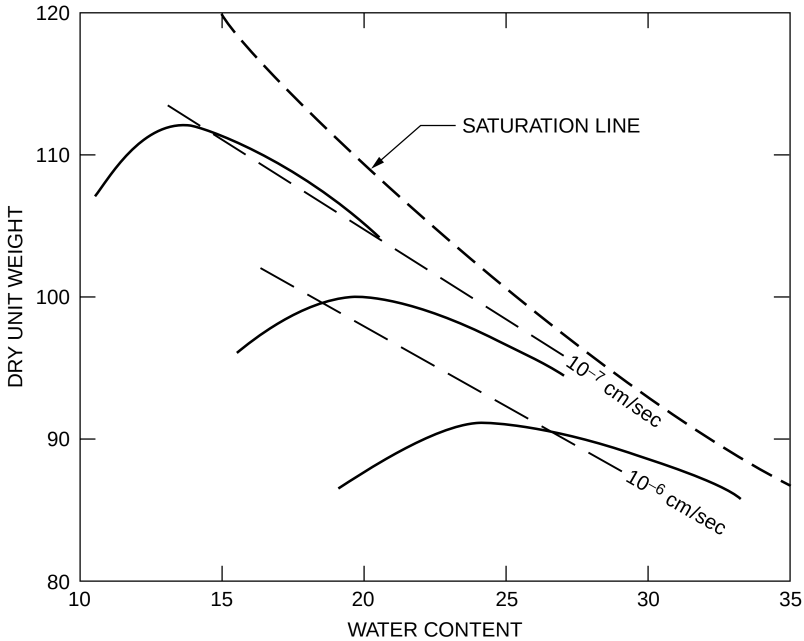

FIGURE 26.8 Permeability window.

- Finally, the permeability window is selected as the area bound by the isopermeability line corresponding to the required permeability and the saturation line. Additionally, the permeability window is generally truncated by moisture content lower and upper bounds. The line of optimums is generally selected as the moisture content lower bound, because cohesive soils compacted dry of optimum are too rigid and may easily crack. The moisture content upper bound is selected based on unconfined strength and compressibility, depending on the specific application.

It should be noted that selecting moisture contents on the Proctor curves and compacting the specimens following the Proctor procedure does not provide points on a grid. However, this procedure is preferred because the compaction procedure is uniform and considered to be more representative of the field procedures. Some laboratories prefer to prepare the specimens following a rectangular grid on the dry density–moisture graph, compacting the specimens within a mold using a jack. In these cases the procedure is less representative of the field conditions and some differences can be expected with respect to tests performed on specimens prepared using Proctor procedures.

The discussion presented above refers, in general, to tests in which the permeant is clean water. However, in geo-environmental applications, the permeant is leachate in the case of liners. The flow of leachate through cohesive soils may produce changes in the cations, which in turn may affect the permeability of the soil. In order to evaluate these changes, leachate compatibility permeability tests are performed as described below.

Leachate compatibility permeability tests are long-duration permeability tests, in which distilled water is used initially as the permeant and then leachate from the facility (or a similar leachate) is used as the permeant. These tests are continued until several pore volumes (typically three or four) of leachate have circulated through the specimen. During this period changes in the permeability of the soil are monitored. A leachate compatibility permeability test of a low-permeability soil generally lasts several months.

Drainage Layers

Drainage layers constructed of natural soils consist of sands or gravels, and may be used in liners or covers. Drainage layers are designed to have a hydraulic capacity adequate to convey the design flow rate without significant head buildup. The hydraulic capacity of a drainage layer is a function of its permeability, thickness, and slope. Frequently the transmissivity, defined as the product of the permeability by the thickness, is used. The main considerations regarding drainage layers are listed below:

The gradation of the granular soil to be used for a drainage layer is selected based on the required permeability. In general, there are no strict gradation requirements, since the requirements for filtration between adjacent soil layers are satisfied by means of a geotextile acting as a filter. Frequently, gradation requirements, are driven mostly by availability (i.e., aggregates commercially available).

Drainage layers in liner systems must resist the attack of leachate, which is generally acidic. Therefore calcareous granular soils must be avoided.

Drainage layers are frequently adjacent to geomembranes, which are susceptible to puncture. Geotextiles are used to protect geomembranes from granular soils. However, if gravel-size soil is used, geotextiles may not provide sufficient protection from angular gravel. Therefore, the maximum angularity of gravels is generally limited to subangular.

The minimum drainage layer thickness that can be practically constructed is approximately six inches. However, if the drainage layer has to be placed on a geomembrane, driving construction equipment on the drainage layer may seriously damage the geomembrane. In these cases placement considerations control the minimum layer thickness and must be carefully evaluated.

Fill

The requirements for fills are, in general, similar to those for other types of engineering projects. The following types of fills are frequent in geo-environmental projects:

- *Grading fill*. There are no strict requirements for grading fills in which fill slopes are not constructed. Depending on the thickness of the fill and the loads to be applied on them, compressibility may be an important consideration. When grading fill is used to form fill slopes, coarse granular soil is used to provide adequate shear strength.
- *Structural fill*. This category comprises fill used for elements such as intercell berms and perimeter berms in landfills, or perimeter berms for leachate ponds. When these elements will be subjected to significant lateral pressures, these berms are constructed of coarse granular soils. These berms are generally lined, so permeability is not an issue.
- *Water-containment berms fill*. Berms containing water-retaining structures, such as sedimentation and detention basin berms, require a combination of low permeability and high shear strength. These two conditions are difficult to satisfy simultaneously, since soils of low permeability are weak, and vice versa. In these cases the type of fill generally used consists of a granular soil with significant fines content, which provides intermediate permeability and shear strength. Alternatively, lined berms may be constructed.

Vegetative Layer

As explained previously, the vegetative layer is the uppermost layer of a cover system. Vegetative layers must be adequate to support vegetation, generally grass, and must have adequate resistance to erosion.

In order to support vegetation, the soil must contain sufficient nutrients. Nutrients can also be supplied by adding limestone or other fertilizers. For information about this topic, consult the state erosion and sediment control manual or the country Soil Conservation District, since the requirements vary as a function of climate.

The erosion that a vegetative layer may suffer is a function of the soil type and the slope inclination and length. The soil loss is estimated by means of the Universal Soil Loss Equation, published by the U.S. Department of Agriculture. The maximum soil loss recommended by the U.S. Environmental Protection Agency for landfill covers is 2 tons/acre/year.

It should be noted that specifications frequently refer to vegetative layers as "topsoil." The term *topsoil* has a specific meaning from an agricultural point of view and is generally more expensive than other soils that can also support vegetation with adequate fertilization. For these reasons, it is recommended to use the term *topsoil* only when that type of soil is specifically required.

Geosynthetics

A large number of geosynthetic materials are used in environmental applications and there are many different tests to characterize their properties. This prevents a detailed presentation within the space allocated in this section. Therefore this section presents a brief summary of the most common types of geosynthetic materials generally used in environmental applications and their properties. For a detailed discussion on the applications and testing of geosynthetic materials, product data, and manufacturers, Koerner [1994], GRI and ASTM test methods and standards, and the Specifier's Guide of the Geotechnical Fabrics Report [Industrial Fabrics Association International, 1993] are recommended.

In general, two types of test are included in geosynthetic specifications: conformance tests and performance tests. Conformance tests are performed prior to installing the geosynthetics, to demonstrate compliance of the materials with the project specifications; some of the conformance tests are frequently provided by the manufacturer. Performance testing is done during the construction activities, to ensure compliance of the installed materials and the installation procedures with the project specifications.

Barrier Layers

Geosynthetic barrier layers may consist of geomembranes, also called flexible membrane liners (FMLs), or geosynthetic clay liners (GCLs).

As discussed previously, geomembranes are used as barrier layers for landfill liner and cover systems. They are also used as canal liner, surface impoundment liner and cover, tunnel liner, dam liner, and leach pad liner. In general, geomembranes are classified with respect to the polymer that they are made of and their surficial roughness. These two classifications are discussed below.

The most common polymers used for geomembranes are high density polyethylene (HDPE), very low density polyethylene (VLDPE), polypropylene, and PVC. Selection of the polymer is based primarily on chemical resistance to the substances to be contained. The polymer most widely used for landfill liner systems is HDPE, since it has been shown to adequately resist most landfill leachates. In the case of cover system barrier layers, flexibility is frequently an important selection factor, since landfill covers are subjected to significant settlements. VLDPE geomembranes are generally more flexible than HDPE and therefore are frequently used for cover systems.

The chemical resistance of geomembranes and other geosynthetic materials is evaluated by means of the EPA 9090 Compatibility Test. In this test, the initial physical and mechanical properties of a geosynthetic are determined (baseline testing) prior to any contact with the chemicals to be contained (leachate in the case of landfills). Then, geosynthetic specimens are immersed in tanks containing those chemicals, at 23 and 50°C. Specimens are removed from the tanks after 30, 60, 90, and 120 days of immersion and tested to determine their physical and mechanical properties. Comparison of these properties with the results of the baseline testing serves as an indicator of the effect of the chemicals on that specific geosynthetic material.

With respect to surface roughness, geomembranes are classified as smooth or textured. Smooth geomembranes are less expensive and easier to install than textured geomembranes, but exhibit a low interface friction angle (as low as 6 to 8 degrees) with other geosynthetics and with cohesive soils. Textured geomembranes provide a higher interface friction angle. The reader is warned that interface friction angles are not fixed values and must be evaluated on a case-specific basis, since they vary with parameters such as relative displacement (peak versus residual strength), normal stress, moisture conditions, backing used in the test (soil or rigid plates), and so on.

The main physical and mechanical properties generally used to characterize geomembranes and the test procedures to measure those properties are as follows:

Thickness	ASTM D751 and D1593
Density	ASTM D1505
Tensile properties	ASTM D638
Yield strength	
Break strength	
Elongation at yield	
Elongation at break	

Puncture resistance	FTMS 101C method 2065
Tear resistance	ASTM D1004
Low-temperature brittleness	ASTM D746
Carbon black content	ASTM D1603
Environmental stress crack resistance	ASTM D5397

Seaming of geomembranes is performed by bonding together two sheets. The main methods for seaming geomembranes are:

- *Extrusion welding*. A ribbon of molten polymer is extruded on the edge of one of the sheets or in between the two sheets. This method is applicable only to polyethylene and polypropylene geomembranes.
- *Thermal fusion*. Portions of the two sheets are melted using a hot wedge or hot air. This method is applicable to all types of geomembranes.
- *Solvent or adhesive processes*. These methods are not applicable to polyethylene and polypropylene geomembranes.

Seam strength (shear and peel) of geomembranes is controlled during installation by means of performance (destructive) testing performed in accordance with ASTM D4437 procedures.

GCLs consist of a thin layer of bentonite sandwiched between two geotextiles or bonded to a geomembrane. GCLs are currently available under the following registered names: Gundseal, Claymax, Shear-Pro, Bentofix, Bentomat, and NaBento. Gundseal is manufactured with a geomembrane on one side only, while the other products have geotextiles on both sides. The geomembrane and geotextiles are fixed to the bentonite layer by means of adhesives, needle-punched fibers, or stitches. The types of geotextiles used include several combinations of woven and nonwoven geotextiles.

The main physical and mechanical properties generally used to characterize GCLs and the test procedures to perform those tests are as follows:

Bentonite mass per unit area	ASTM D3776
GCL permeability	ASTM D5084
Base bentonite properties	
Moisture content	ASTM D4643
Swell index	USP-NF-XVII
Fluid loss	API 13B
Geotextiles	
Weight	ASTM D3776
Thickness	ASTM D1593
GCL tensile strength	ASTM D4632
Percent elongation	ASTM D463

Evaluation of the strength of a GCL must take into account its internal shear strength and the interface strength between the GCL and adjacent materials. The reader is warned that both the internal and interface shear strengths are not fixed values and must be evaluated on a case-specific basis, since they vary with parameters such as relative displacement (peak versus residual strength), normal stress, hydration of the bentonite, backing used in the test, and so on. Special attention must be given to the effects of long-term shear (creep) on needle-punched fibers and stitches, and to the squeezing of hydrated bentonite through the geotextiles. Seaming of GCLs is performed by overlapping adjacent sheets.

Drainage Layers

Geosynthetic drainage layers used as part of liner and cover systems may consist of geonets or geocomposites. Geocomposites consist of a geonet with factory-welded geotextile on one side or on both sides.

Polymers used for geonets are polyethylene (PE), HDPE, and medium density polyethylene (MDPE). The EPA 9090 Compatibility Test is also used to evaluate the chemical resistance of geonets and geocomposites. Geotextiles of various types and weights are attached to geonets to manufacture geocomposites, the most common type being nonwoven.

The main physical, mechanical, and hydraulic properties generally used to characterize geonets and geocomposites, and the test procedures to measure those properties, are thickness (ASTM D5199), compressive strength at yield (ASTM D1621), and in-plane flow rate [transmissivity (ASTM D4716)]. The most important property of geonets and geocomposites, in relation to their performance as drainage layers, is the transmissivity. The reader is warned that the results of laboratory transmissivity tests on geonets and geocomposites vary with several parameters, including normal stress, gradient, the type and weight of geotextiles attached, and the backing used in the tests. Furthermore, transmissivity values determined in short-term laboratory tests must be decreased, applying several correction factors to calculate long-term performance values. These correction factors account for elastic deformation of the adjacent geotextiles into the geocomposite core space, creep under normal load, chemical clogging and/or precipitation of chemicals, and biological clogging. A complete discussion of the correction factors recommended for various applications is presented by Koerner [1990].

In addition to the properties of the geonet or geocomposite, the properties of the geotextiles attached to the geonet are generally specified separately as discussed below. Seaming of geonets and geocomposites is generally performed using plastic ties, which are not intended to transfer stresses.

Geotextiles

Geotextiles may be used to perform several different functions. The most important are:

- *Separation*. Consists of providing separation between two different soils to prevent mixing. A typical application is placement of a granular fill on a soft subgrade.
- *Reinforcement*. Applications of geotextiles for reinforcement are identical to those of geogrids, discussed in the next section.
- *Filtration*. The geotextile is designed as a filter to prevent migration of soil particles across its plane. Several aspects need to be considered associated with this function: filtration (opening size relative to the soil particles), permittivity (flow rate perpendicular to the geotextile), and clogging potential.
- *Drainage*. In-plane capacity to convey flow or transmissivity.
- *Cushioning/protection*. The geotextile serves to separate a geomembrane from a granular soil, to protect the geomembrane from damage.

Geotextiles are classified with respect to the polymer that they are made of and their structure. The polymers most commonly used to manufacture geotextiles are polypropylene and polyester. With respect to their structure geotextiles are classified primarily as woven or nonwoven. Each of these types of structure is in turn subdivided, depending on the manufacturing process, as follows: woven (monofilament, multifilament, slit-film monofilament, slit-film multifilament); or nonwoven (continuous-filament heat bonded, continuous-filament needle punched, staple needle punched, spun bonded, or resin bonded).

The main physical, mechanical, and hydraulic properties generally used to characterize geotextiles and the test procedures to measure those properties are:

Specific gravity	ASTM D792 or D1505
Mass per unit area	ASTM D5261
Percent open area (wovens only)	CWO-22125
Apparent opening size	ASTM D4751
Permittivity	ASTM D4491
Transmissivity	ASTM D4716
Puncture strength	ASTM D4833
Burst strength	ASTM D3786
Trapezoid tear strength	ASTM D4533
Grab tensile/elongation	ASTM D4632
Wide-width tensile/elongation	ASTM D4595
UV resistance	ASTM D4355

Seaming of geotextiles is performed by sewing. Seam strength is tested following ASTM D4884.

Most geotextiles are susceptible to degradation under ultraviolet light. Therefore, appropriate protection is required during transport, storage, and immediately after installation.

Geogrids

Geogrids are used to provide tensile reinforcement. Typical applications include:

- *Reinforcement of slopes and embankments*. Potential failure surfaces would have to cut across layers of geogrid. The resisting forces on the potential failure surface would be comprised of the shear strength of the soil and the tensile strength of the geogrid.
- *Reinforcement of retaining walls*. In this application, some of the soil pressure that would act against the retaining wall is transferred by friction to the part of the reinforcing geogrid layer adjacent to the wall, while the rest of the geogrid (away from the wall) provides passive anchorage.
- *Unpaved roads*. The stiffness of the geogrid allows distribution of loads on a larger area and prevents excessive rutting.
- *Reinforcement of cover systems*. A potential mode of failure of relative steep covers is sliding of a soil layer on the underlying layer (veneer-type sliding). To control this type of failure, a geogrid layer is embedded within the unstable soil layer to provide a stabilizing tensile force. The opposite side of the geogrid must be anchored or must develop sufficient passive resistance to restrain its displacement.
- *Bridging of potential voids under liner systems*. When liner systems are constructed on existing waste (vertical expansions) or in areas where sinkholes may develop, geogrids are used within the liner system to allow bridging of voids.

Geogrids are made of polyester, polyethylene, and polypropylene. If exposed to waste or leachate, selection of the polymer is based on chemical resistance, as in the case of geomembranes. Depending on the direction of greater strength and stiffness, geogrids are classified as uniaxial or biaxial.

The main physical and mechanical properties generally used to characterize geogrids and the test procedures to measure those properties are mass per unit area (ASTM D5261), aperture size, wide-width tensile strength (ASTM D4595), and long-term design strength (GRI GG4).

Defining Terms

The definitions presented in this section have been extracted from the Code of Federal Regulations (CFR), 40 CFR 258, "EPA Criteria for Municipal Solid Waste Landfills," and 40 CFR 261, "Identification and Listing of Hazardous Waste." Definitions not available in the federal regulations were obtained from the Virginia Solid Waste Management Regulations.

Agricultural waste — All solid waste produced from farming operations, or related commercial preparation of farm products for marketing.

Commercial solid waste — All types of solid waste generated by stores, offices, restaurants, warehouses, and other nonmanufacturing activities, excluding residential and industrial wastes.

Construction/demolition/debris landfill — A land burial facility engineered, constructed, and operated to contain and isolate construction waste, demolition waste, debris waste, inert waste, or combinations of the above solid wastes.

Construction waste — Solid waste which is produced or generated during construction, remodeling, or repair of pavements, houses, commercial buildings, and other structures. Construction wastes include, but are not limited to, lumber, wire, sheetrock, broken brick, shingles, glass, pipes, concrete, paving materials, and metal and plastics if the metal or plastics are part of the materials of construction or empty containers for such materials. Paints, coatings, solvents, asbestos, any liquid, compressed gases or semiliquids, and garbage are not construction wastes.

Cover material — Compactable soil or other approved material which is used to blanket solid waste in a landfill.

Debris waste — Wastes resulting from land-clearing operations. Debris wastes include, but are not limited to, stumps, wood, brush, leaves, soil, and road spoils.

Demolition waste — That solid waste which is produced by the destruction of structures and their foundations and includes the same materials as construction wastes.

Garbage — Readily putrescible discarded materials composed of animal, vegetal, or other organic matter.

Hazardous waste — The definition of hazardous waste is fairly complex and is provided in 40 CFR Part 261, "Identification and Listing of Hazardous Waste." The reader is referred to this regulation for a complete definition of hazardous waste. A solid waste is classified as hazardous waste if it is not excluded from regulations as a hazardous waste; it exhibits characteristics of ignitability, corrosivity, reactivity, or toxicity as specified in the regulations; or it is listed in the regulations (the regulations include two types of hazardous wastes: from nonspecific sources and from specific sources).

Household waste — Any solid waste (including garbage, trash, and sanitary waste in septic tanks) derived from households (including single and multiple residences, hotels and motels, bunkhouses, ranger stations, crew quarters, campgrounds, picnic grounds, and day-use recreation areas).

Industrial solid waste — Solid waste generated by a manufacturing or industrial process that is not a hazardous waste regulated under Subtitle C of RCRA. Such waste may include, but is not limited to, waste resulting from the following manufacturing processes: electric power generation; fertilizer/agricultural chemicals; food and related products/by-products; inorganic chemicals; iron and steel manufacturing; leather and leather products; nonferrous metals manufacturing/foundries; organic chemicals; plastics and resins manufacturing; pulp and paper industry; rubber and miscellaneous plastic products; stone, glass, clay, and concrete products; textile manufacturing; transportation equipment; and water treatment. This term does not include mining waste or oil and gas waste.

Industrial waste landfill — A solid waste landfill used primarily for the disposal of a specific industrial waste or a waste which is a by-product of a production process.

Inert waste — Solid waste which is physically, chemically, and biologically stable from further degradation and considered to be nonreactive. Inert wastes include rubble, concrete, broken bricks, bricks, and blocks.

Infectious waste — Solid wastes defined to be infectious by the appropriate regulations.

Institutional waste — All solid waste emanating from institutions such as, but not limited to, hospitals, nursing homes, orphanages, and public or private schools. It can include infectious waste from health care facilities and research facilities that must be managed as an infectious waste.

Lagoon — A body of water or surface impoundment designed to manage or treat wastewater.

Leachate — A liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from such waste.

Liner — A continuous layer of natural or synthetic materials beneath or on the sides of a storage or treatment device, surface impoundment, landfill, or landfill cell that severely restricts or prevents the downward or lateral escape of hazardous waste constituents, or leachate.

Liquid waste — Any waste material that is determined to contain free liquids.

Litter — Any solid waste that is discarded or scattered about a solid waste management facility outside the immediate working area.

Monitoring — All methods, procedures, and techniques used to systematically analyze, inspect, and collect data on operational parameters of the facility or on the quality of air, groundwater, surface water, and soils.

Municipal solid waste — Waste which is normally composed of residential, commercial, and institutional solid waste.

Municipal solid waste landfill unit — A discrete area of land or an excavation that receives household waste, and that is not a land application unit, surface impoundment, injection well, or waste pile. A municipal solid waste landfill unit also may receive other types of RCRA Subtitle D wastes, such as commercial solid waste, nonhazardous sludge, small quantity generator waste, and industrial solid waste. Such a landfill may be publicly or privately owned.

Putrescible waste — Solid waste which contains organic material capable of being decomposed by microorganisms and causing odors.

Refuse — All solid waste products having the character of solids rather than liquids and which are composed wholly or partially of materials such as garbage, trash, rubbish, litter, residues from cleanup of spills or contamination, or other discarded materials.

Release — Any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injection, escaping, leaching, dumping, or disposing into the environment solid wastes or hazardous constituents of solid wastes (including the abandonment or discarding of barrels, containers, and other closed receptacles containing solid waste). This definition does not include any release which results in exposure to persons solely within a workplace; release of source, by-product, or special nuclear material from a nuclear incident, as those terms are defined by the Atomic Energy Act of 1954; and normal application of fertilizer.

Rubbish — Combustible or slowly putrescible discarded materials which include but are not limited to trees, wood, leaves, trimmings from shrubs or trees, printed matter, plastic and paper products, grass, rags, and other combustible or slowly putrescible materials not included under the term *garbage*.

Sanitary landfill — An engineered land burial facility for the disposal of household waste which is located, designed, constructed, and operated to contain and isolate the waste so that it does not pose a substantial present or potential hazard to human health or the environment. A sanitary landfill also may receive other types of solid wastes, such as commercial solid waste, nonhazardous sludge, hazardous waste from conditionally exempt small-quantity generators, and nonhazardous industrial solid waste.

Sludge — Any solid, semisolid, or liquid waste generated from a municipal, commercial, or industrial wastewater treatment plant, water supply treatment plant, or air pollution control facility exclusive of treated effluent from a wastewater treatment plant.

Solid waste — Any garbage (refuse), sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility, and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations and from community activities. Does not include solid or dissolved materials in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges that are point sources subject to permit under 33 U.S.C. 1342, or source, special nuclear, or by-product material as defined by the Atomic Energy Act of 1954, as amended.

Special wastes — Solid wastes that are difficult to handle, require special precautions because of hazardous properties, or the nature of the waste creates management problems in normal operations.

Trash — Combustible and noncombustible discarded materials. Used interchangeably with the term *rubbish*.

Vector — A living animal, insect, or other arthropod which transmits an infectious disease from one organism to another.

Washout — Carrying away of solid waste by waters of the base flood.

Yard waste — That fraction of municipal solid waste that consists of grass clippings, leaves, brush, and tree prunings arising from general landscape maintenance.

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