

## CHAPTER 24

# Geoenvironmental Engineering

This chapter introduces a relatively recent yet very important field: geoenvironmental engineering. The book by Sharma and Reddy (2004) is an excellent reference for further study.

### 24.1 INTRODUCTION

After World War II, there was a remarkable development of industries aimed at improving the quality of life. These chemical and manufacturing industries created a significant amount of waste in an unregulated environment. The advent of nuclear power plants in the late 1950s brought the problem of nuclear wastes, which can remain deadly for thousands of years. Disposal of such deadly wastes caught the attention of the public and emphasized the need for a more organized approach. The Love canal disaster occurred when an old canal that had been filled with toxic chemicals for many years started to leak and seriously affect the health of local residents in New York State in the 1970s. This broadly publicized disaster contributed to the development of laws and regulations aimed at ensuring the health and safety of the public by avoiding any environmental contamination.

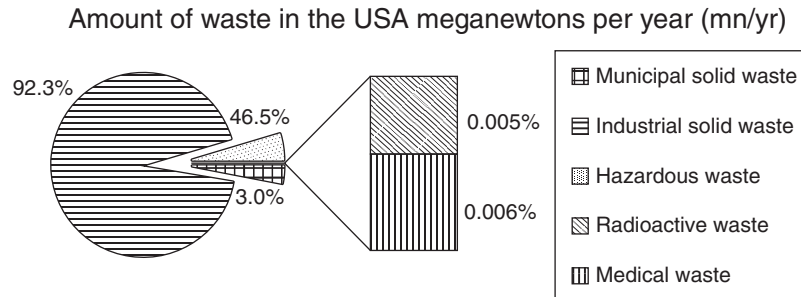
### 24.2 TYPES OF WASTES AND CONTAMINANTS

Wastes are unwanted or useless materials. They come from many different human activities and take many different forms. Sources of wastes include dredging, mining, and farming; they can also be generated by the residential, commercial, institutional, industrial, nuclear power, and defense sectors. The waste generated by those human activities amounts to something like 100 billion kN or 10 billion m<sup>3</sup> per year worldwide. Wastes can be in gas form, liquid form, or solid form. In geotechnical engineering, the liquid and gas forms are of concern because they propagate through the soil that must be cleaned up; this falls under the topics of *contamination* and *remediation*. The solid wastes, hazardous or not, end up being stored in landfills or other facilities designed for that purpose. In the United States alone, the amount of waste generated each year is staggering, as shown in Figure 24.1.

Waste	Meganewtons per Year (MN/YR)
Municipal solid waste	2,500,000
Industrial solid waste	76,000,000
Hazardous waste	3,800,000
Radioactive waste	3,750
Medical waste	4,650

Wastes can be categorized in the following different types (Sharma and Reddy 2004):

1. *Solid wastes*. The term *solid waste* is misleading, as a solid waste can be a solid, a liquid, or a gas. These wastes include municipal solid waste (MSW), industrial solid wastes, and construction and demolition wastes. MSW includes household solid wastes and commercial solid wastes. Figure 24.2 shows the distribution of MSW in percent of the total quantity and its evolution over the past 50 years in the United States. Industrial solid wastes are nonhazardous wastes generated by manufacturing and industrial processes, including the production of furniture, apparel, machinery, busses, trucks, cars, airplanes, jewelry, shoes, and so on. Construction and demolition wastes include wood, concrete, bricks, and plumbing materials, among others.
2. *Hazardous wastes*. These are wastes that can cause death or serious illness or pose a substantial hazard to human health or the environment. In the United States, they are defined in subtitle C of the Resource Conservation and Recovery Act (RCRA). The Environmental Protection Agency (EPA) distinguishes three categories of hazardous wastes: nonspecific source wastes (e.g., solvents, dioxins), specific source wastes (e.g., sludge from petroleum refining and organic chemical manufacturing), and commercial chemical product source waste (e.g., creosote, acids, pesticides). Another important factor is the concentration level of the chemical in



**Figure 24.1** Amount of waste per year in the United States (After Sharma and Reddy 2004)



**Figure 24.2** Distribution of MSW and its evolution.

the liquid (water); the acceptable level is defined in the regulations. For example, 0.05 milligram of mercury per liter would be acceptable but 0.3 mg/L would not; 1 mg of lead per liter would be acceptable but 7 mg/L would not.

3. **Radioactive waste.** These wastes are classified into four categories of their own:
  - a. High-level wastes (HLW). These are liquid or solid wastes that are extremely dangerous and must not come into contact with humans. They come from defense or nuclear power plant activities. They require permanent isolation, as the radiation penetration remains lethal for 10,000 years.
  - b. Transuranic wastes (TRU). These come from manufacture of nuclear weapons and processing of nuclear fuels. The radiation penetration remains lethal for 20 years. TRUs are relatively rare.
  - c. Low-level wastes (LLW). These are the lowest-level radioactive wastes, which can be disposed of as regular waste after sufficient isotope decay.
  - d. Mill tailings. These are the ore residues from mining uranium. There is a significant amount of it and it is typically stored, sometimes buried in large remote areas of a country.
4. **Medical waste.** These wastes come from hospitals and other health agencies. They include microbiological wastes (e.g., infectious cultures), human blood,

pathological wastes (e.g., organs, body parts), contaminated animal wastes, isolation wastes (e.g., waste contaminated with highly communicable diseases), contaminated sharps (e.g., needles, scalpels), and uncontaminated sharps. Some MSW, such as disposable diapers and sanitary napkins, do contain pathogens, but usually not as much as medical wastes. One common solution for medical wastes is incineration to kill the disease-causing pathogens.

### 24.3 LAWS AND REGULATIONS

In the United States, once a bill is proposed, passes both Houses of Congress, and is signed by the president, it becomes a law (also known as an act or statute). To enforce the new act, the responsible agency—the Environmental Protection Agency in most cases for geoenvironmental engineering—develops regulations to implement the act. All federal government regulations are collected in enormous books of the *Code of Federal Regulations*; this series of books is divided into volumes called titles (Title 40 covers topics relating to geoenvironmental engineering) which are further divided into parts and then sections. The EPA also develops Guidance Documents for technical issues and Policies for decision management to help industry comply with the regulations. Each state can use the federal regulations as is or enforce stricter, state-specific versions. The EPA office in each state is in charge of enforcing the regulations.

Laws have been passed on a wide variety of environmental topics. Some of the most important and with the widest range include:

- Solid Waste Disposal Act (SWDA; 1965, 1970)
- National Environmental Policy Act (NEPA; 1969)
- Occupational Safety and Health Act (OSHA; 1970)
- Clean Air Act (CAA; 1970, 1977, 1990)
- Clean Water Act (CWA; 1977, 1981, 1987)
- Safe Drinking Water Act (SDWA; 1974, 1977, 1986)
- Resource Conservation and Recovery Act (RCRA; 1976, 1980)
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA; 1980)

These laws have positively impacted geoenvironmental engineering practice. In particular, CERCLA, also known as Superfund, generated a tremendous amount of work for geotechnical engineers regarding the cleaning of soil deposits. As society evolves and humankind creates new products, new laws are enacted and amendments are made to existing acts. This is the case of the Hazardous and Solid Waste Amendments to RCRA (HSWA; 1984) and the Superfund Amendments and Reauthorization Amendments to CERCLA (SARA; 1986). CERCLA/Superfund addressed the issue of cleaning up contaminated sites, whereas RCRA addressed the issue of landfill design.

Safety and health are the top priority regarding investigation and remediation at contaminated sites. The following levels of protection for humans working on contaminated sites have been formulated by the Occupational Safety and Health Administration (OSHA) in the United States. They address the level of protection required for eye, skin, and respiratory safety (Table 24.1).

1. *Level D*. Minimum protection including coveralls, gloves, chemical-resistant steel-toed boots, safety glasses, hard hat, escape mask, and face shield.
2. *Level C*. Moderate protection, including full-face or half-mask, air-purifying respirator, hooded chemical-resistant clothing, inner and outer chemical-resistant gloves, chemical-resistant boots and boot covers, hard hat, escape mask, and face shield.
3. *Level B*. Very high protection, including positive-pressure, full-face, self-contained breathing apparatus

(SCBA), hooded chemical-resistant clothing, chemical-resistant inner and outer gloves, chemical-resistant steel-toed boots and boot covers, hard hat, and face shield.

4. *Level A*. Maximum protection, including positive-pressure, full-face, self-contained breathing apparatus (SCBA), totally encapsulating chemical-protective suit, chemical-resistant inner and outer gloves, chemical-resistant steel-toed boots and boot covers, and hard hat (under suit).

## 24.4 GEOCHEMISTRY BACKGROUND

### 24.4.1 Chemistry Background

A discussion of geochemistry starts with a background on chemistry. Electrons, protons, and neutrons make up the universe. They are extremely small subatomic particles with masses of  $1.66 \times 10^{-27}$  kg for neutrons and protons and  $9.1 \times 10^{-31}$  kg for the much lighter electron. Electrons are negatively charged, protons are positively charged, and neutrons are electrically neutral. Atoms, which consist of electrons, protons, and neutrons in various combinations, are the basic building blocks of matter. Hydrogen, oxygen, and carbon, for example, are atoms. You can break them down into smaller pieces, but you will no longer have hydrogen, oxygen, or carbon. The nucleus of the atom is made of neutrons and protons, while electrons gravitate around the nucleus. An *element* is made of only one kind of atom. The periodic table (Figure 24.3) in chemistry gives the list of the different elements, 92 of which occur naturally (e.g., hydrogen, oxygen, carbon) and some two dozen others of which have been created by scientists. By changing the number of protons and electrons in the atom, you create different elements. For example, oxygen has 8 protons, but hydrogen has only 1. This is an element's *atomic number*. The periodic table gives the atomic number (number of protons in the nucleus) and the atomic mass, which is the sum of the weight of the protons and the neutrons times the Avogadro number. (Amadeo Avogadro was an Italian scientist who contributed significantly to molecular theory in the early 1800s.) Note that the weight of the electrons is negligible compared to the weight of the protons and neutrons. Stable atoms have the same number of electrons and protons.

The Avogadro number ( $6.022 \times 10^{23}$ ) is the number of atoms in 12 grams of carbon-12. This number helps define the mole. In biology a *mole* is an underground rodent, but in chemistry it is the mass corresponding to  $6.022 \times 10^{23}$  (Avogadro number) molecules, atoms, or some other pure chemical substance unit. The periodic table gives the mass of one mole of each of the elements. For example, a mole of water ( $H_2O$ ) has a mass of two moles of hydrogen ( $2 \times 1.00794$  g) plus one mole of oxygen (15.9994 g) or 18.01528 g. Note that, in chemistry, mass is calculated with a much larger number of significant figures than in geotechnical engineering. The

**Table 24.1 Levels of Safety and Health Protection (OSHA)**

Protection	Level A	Level B	Level C	Level D
Respiratory	Maximum	Maximum	Moderate	Minimum
Skin	Maximum	Very high	Moderate	Minimum
Eye	Maximum	Very high	Moderate	Minimum

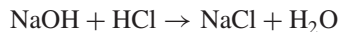


The pH, a measure of acidity, gives the concentration of hydrogen ions by:

$$\text{pH} = -\log(\text{H}^+) \quad (24.2)$$

where log is the logarithm base 10 and  $(\text{H}^+)$  is the concentration of hydrogen ions in moles per liter of solution—or, more accurately, the hydrogen ions' activity, which can be slightly different. The pH scale varies from 0 to 14, with a neutral solution (distilled water) having a pH of 7. A pH less than 7 is acidic and more than 7 is basic or alkaline. Example of pH values include battery acids pH = 1, vinegar and lemon juice 2.5, wine 3.2, beer 4, human blood 7, baking soda 8.5, soap 10, and ammonia 12. The p in pH is said to stand for *potential* and pH for *potential of hydrogen*.

Chemical reactions take place when reactants are transformed into products. For example:



Sodium Hydroxide + Hydrochloric Acid  $\rightarrow$  Salt + Water  
(24.3)

These chemical reactions must satisfy conservation of mass on both sides of the reaction equation. There are at least four types of chemical reactions:

1. *Acid-base reaction*. These reactions affect the pH of the soil and groundwater. Eq. 24.3 is an example.
2. *Precipitation-dissolution reactions*. Some chemicals are more soluble (sugar and salt) in water than others (oil). This is important in geoenvironmental engineering, as it can affect a remedial operation.
3. *Oxidation-reduction reactions* (redox reactions). *Oxidation* is the loss of electrons by a molecule, atom, or ion. *Reduction* is a gain of electrons. For example, oxidation of carbon can produce carbon dioxide,  $\text{CO}_2$ , but reduction of carbon can produce methane,  $\text{CH}_4$ . Both gases are produced by the long-term degradation of landfills.
4. *Complexation reactions*. These are chemical reactions that take place between a metal ion and a molecular or ionic entity known as a *ligand*. The properties of these complexes, including solubility, can be quite different from the properties of the metal itself, and such transformations can help in cleanup strategies.

Inorganic chemistry and organic chemistry are two very important branches of chemistry. The difference between organic and inorganic compounds is that most organic compounds contain carbon, whereas most inorganic compounds do not. Carbon is the fourth most abundant element on and in our planet, and organic compounds vastly outweigh (100 to 1?) inorganic compounds. Living organisms, petroleum and its derivatives, plastics, rubber, fat, sugar, proteins, and enzymes are examples of organic compounds. Metals and salt

are examples of inorganic compounds. Nuclear chemistry is another branch of chemistry. Elements with high atomic numbers, like uranium, tend to be unstable and break down. During this process, these elements, called *radionuclides*, emit radiation ( $\alpha$  rays,  $\beta$  rays,  $\gamma$  rays) with an intensity that decays very slowly. A radionuclide is characterized by its half-life, which is the time required for 50% of the atoms in a substance to decay into more stable substances. All these aspects of chemistry are important to the geoenvironmental engineer who wishes to select the best response possible to contamination and disposal problems.

#### 24.4.2 Geochemistry Background

*Geochemistry* is the application of chemistry to the field of geoenvironmental engineering. It is concerned with the interaction between chemicals and soils at temperatures and pressures associated with soil deposits.

From the point of view of inorganic chemistry, contamination of soils by toxic metals is the main issue. These toxic metals include, for example, lead (Pb), mercury (Hg), and arsenic (As). They can be dissolved in the pore water (aqueous phase), attached to the particle surface (adsorbed phase), or stuck in the pores as separate solids (solid phase). The geochemical processes controlling the distribution of metals among the three phases include the four chemical reactions mentioned in section 24.4.2, plus adsorption and desorption. *Adsorption* is the accumulations of ions on the charged surface of soil particles; *desorption* is the decrease of ions on the particle surface. The impact of each of these geochemical processes on the contaminant and the soil should be carefully evaluated before any remediation decision is made. This can be done on samples in the laboratory or by computation and modeling.

The total concentration of metal in soil is obtained by washing the soil with an acid and using atomic absorption spectrophotometry (AAS), for example, to study the leachate. The toxicity characteristics leaching procedure (TCLP) simulates the leaching that a waste might undergo when disposed of in a landfill. The TCLP is used to determine if a waste is hazardous or not and to determine the necessary level of treatment if it is hazardous. The different types of metals present in the soil can be identified by sequential extraction, which consists of using solutions of increasing strength and analyzing the leachate. The metal concentration is the mass of metal divided by the mass of dry soil expressed in mg/kg or ppm (parts per million) or in  $\mu\text{g}/\text{kg}$  or ppb (parts per billion).

From the point of view of organic chemistry, contamination of soils by hydrocarbons is the main issue. These hydrocarbons include, for example, benzene, toluene, and xylene. Organic contaminants also include polychlorinated biphenyls (PCBs), and pesticides (aldrin, endrin). A commonly encountered group of hydrocarbon contaminants is the nonaqueous phase liquids (NAPLs), which do not mix with water (e.g., oil). NAPLs are further separated into those that float on water, called light NAPLs or LNAPLs; and those that sink

through water, called dense NAPLs or DNAPLs. LNAPLs typically come from spills of fuels like gasoline, kerosene, or diesel, whereas DNAPLs come from degreasing, metal stripping, and pesticide manufacturing.

NAPLs are found in soils in the gas phase, in the liquid phase, and attached to the surface of the particle. Transformation from one phase to another involves volatilization (liquid to gas), dissolution (mixing in water), adsorption (attachment to particle surface), and biodegradation. *Biodegradation* is a redox reaction that is particularly suited to the action of microbes on NAPLs dissolved in water. The properties of NAPLs are studied in the laboratory and include density, viscosity, solubility, volatility, and surface tension. These properties all affect the optimization of the remedial measure. One way to quantify the amount of NAPLs in soils is to measure the NAPLs degree of saturation  $S_{NAPL}$ , defined as:

$$S_{NAPL} = \frac{V_{NAPL}}{V_v} \quad (24.4)$$

where  $V_{NAPL}$  is the volume of NAPLs in the voids and  $V_v$  is the total volume of voids. Another way to find out how many NAPLs are in the soil is to wash the soil with a solvent and then analyze the solution obtained by a process such as gas chromatography-mass spectrometry (GC-MS).

## 24.5 CONTAMINATION

### 24.5.1 Contamination Sources

Contamination can be due to sources on the ground surface, in the zone above the water table (vadose zone; *vadosus* means shallow in Latin), or in the zone below the water table. On the ground surface, sources include infiltration of contaminated surface water, land disposal of liquid or solid wastes, accidental spills, fertilizers, pesticides, disposal of sewage, wastewater treatment plant sludge, salt used on roads in icy conditions, animal feedlots, and fallout from automobile emissions. In the vadose zone, sources include landfills, surface impoundments, leakage from underground storage tanks (e.g., service station tanks and septic tanks), leakage from underground pipelines, and disposal at the bottom of shallow excavations. Below the groundwater level, sources include deep well injections, mines, abandoned oil wells, and disposal in deep excavations. Both the soil particles and the groundwater can potentially be contaminated, and the most serious contaminants are heavy metals, hydrocarbons, and radionuclides. Although the total contaminated land area may be a fraction of a percent of a country's total surface, it is important to remediate all sites. The cost of remediation can be very high, with an estimated average in the range of \$1 million per site. As there are some hundreds of thousands of such sites, the cost could potentially reach hundreds of billions of dollars. Whatever the cost, and wherever the site, the cleanup or remediation process starts with detection of the contamination.

### 24.5.2 Contamination Detection and Site Characterization

The following are the steps in the remediation process:

1. Detection of the contamination
2. Establishment of the vertical and horizontal extent of the contamination
3. Identification of the contaminants
4. Assessment of the risk and impact
5. Choice and design of the remediation scheme
6. Execution of the remediation work
7. Verification of the solution

Environmental site assessments (ESAs) are part of the detection process. An ESA may be required when purchasing a piece of property in the United States. There are three levels:

*ESA I.* This phase consists of collecting information regarding previous ownership and prior use, using records of contaminated sites in the area, aerial photos, geologic and topographic maps, visit(s) to the site, and talking to neighbors. An ESA I indicates whether there are reasons to believe the site may be contaminated. If so, ESA II comes into play.

*ESA II.* This phase consists of testing the soil and the groundwater to find out if there is contamination and, if so, to what extent and to what level of severity (type of contaminants). If it is found that there is contamination requiring cleanup, ESA III comes into play.

*ESA III.* This phase consists of designing and implementing the remediation scheme, including verification that satisfactory level of cleanup has been achieved.

The plan for an environmental site characterization always includes a Safety and Health plan (S&H) and a Quality Assurance-Quality Control plan (QA-QC). The site characterization can make use of drilling and sampling methods, geophysical methods, or in situ testing methods. Drilling and sampling is described in Chapter 6 for noncontaminated sites. Drilling can be done by hollow stem auger drilling, wet rotary drilling, or air pressure rotary drilling, but the hollow stem auger is usually favored for contaminated sites. The reason is that it can be used dry, and minimizes the amount of contaminated fluid generated and the associated disposal cost. For most levels of contamination, the drill rig must be decontaminated after each boring. This is accomplished by pressure steam-washing the rig and washing the drilling and sampling tools with a strong detergent solution and rinsing with clean water. The purpose of this cleaning process is to avoid cross-contamination between borings. Another difference in the case of contaminated sites is that the drillers have to wear the appropriate level of protection (see section 24.3). The soil samples are the same as in the case of uncontaminated sites, but a much stricter chain of custody is followed for the samples. The *chain of custody* is a documentary trail that follows the sample through its entire life, including when



**Figure 24.4** LED-induced fluorescence cone penetrometer probe. (Courtesy of Vertek, A Division of Applied Research Associates, Inc.)

and where it was taken, who was responsible for it, what happened to it, and everything else, all the way to final disposal. When two people are involved in the transfer of a sample, they both sign and date the chain of custody document.

Geophysical methods are described in Chapter 8 for non-contaminated sites. They are useful for determining the large-scale stratigraphy of the site and therefore the boundaries of the potential contamination. Surface geophysical methods are particularly convenient for contaminated sites because they are nonintrusive.

In situ testing methods are described in Chapter 7 for noncontaminated sites. In the case of contaminated sites, the cone penetrometer is particularly useful because it limits the amount of contaminated cuttings and contaminated water generated during testing. As a result, a number of techniques have been developed for using the CPT at such sites. One of them is the characterization of petroleum-contaminated sites with laser-induced fluorescence or LIF (ASTM D6187). In this test, the CPT probe is equipped with a side window

(Figure 24.4) and a laser beam shines on the soil as the cone is penetrating at 20 mm/s. The laser beam causes the soil and the hydrocarbon to generate fluorescence, which is measured. Each type of hydrocarbon has a “fingerprint” or “signature” signal in terms of intensity and wave length, as shown in Figure 24.5 and Table 24.2. Side-by-side LIF soundings give the extent of the contaminated plume (Figure 24.6).

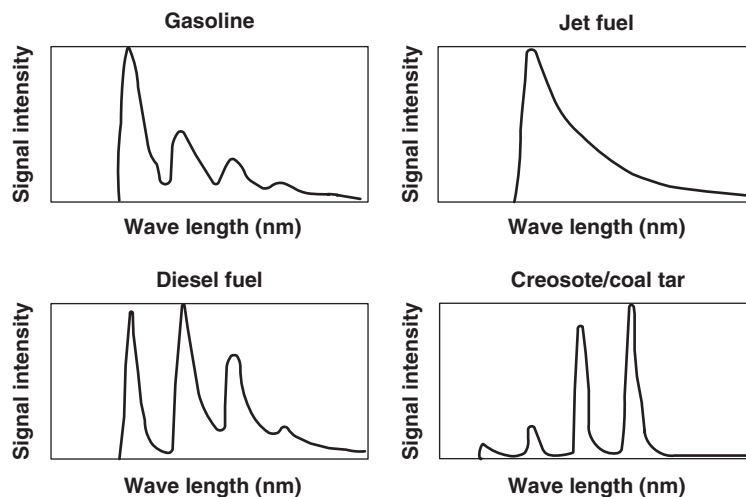
Another CPT technique adapted for contaminated sites is the BAT water sampler (Figure 24.7). BAT is the name of a company. In this case, the CPT probe is equipped with a porous filter that is obstructed until the CPT probe is pushed to the required depth. Then the filter is exposed and water is allowed to penetrate through the filter into a water sampling tube that can be removed through the CPT rods when full. Drawing the water into the sampling tube is accomplished by using the suction of a hypodermic needle.

Yet another CPT technique developed for contaminated sites is the MIP gas sampler (Figure 24.8). MIP stands for *membrane interface probe*. The cone penetrometer probe is

**Table 24.2** Some Values of Fluorescence for Hydrocarbons

Aromatic Hydrocarbon	Molecular Weight (g/mole)	Fluorescence Range (nm)	Fluorescence Color
Toluene	92	270–310	Faint purple
Naphthalene	128	310–370	Blue
Anthracene	178	370–470	Blue-green
Benzo(a)	252	400–500	Green
Pyrene	252	440–530	Green
Perylene	228	470–580	Green-yellow

(Vertek, [www.vertecpt.com/hammerable-fuel-fluorescence-detection-cpt-hydrocarbon-probe](http://www.vertecpt.com/hammerable-fuel-fluorescence-detection-cpt-hydrocarbon-probe))



**Figure 24.5** Fluorescence response of several hydrocarbons. (Courtesy of Fugro.)

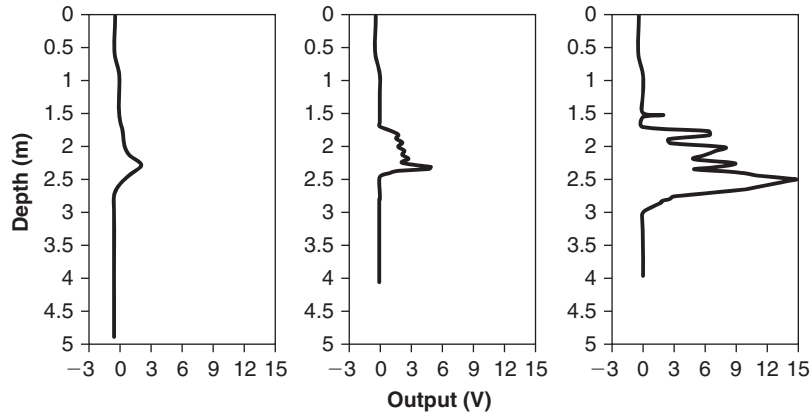


Figure 24.6 LIF CPT soundings and plume identification.

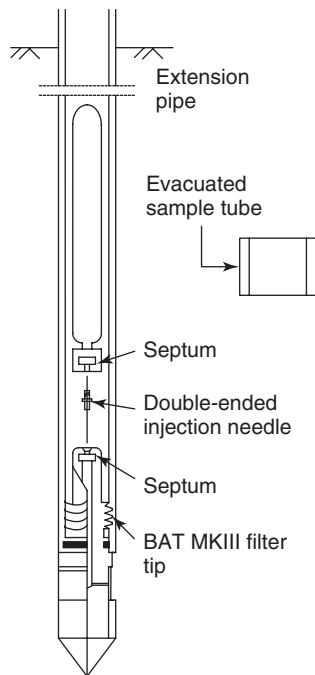


Figure 24.7 BAT CPT water sampler.

fitted with a hydrophobic, semipermeable membrane and a heater. The heater is kept at a temperature higher than  $100^{\circ}\text{C}$  and vaporizes any volatile organic compound (VOC). The natural pressure gradient created by the heat source forces the gas to penetrate through the semipermeable membrane. Once through the membrane, the gas is swept by an inert carrier gas to the surface, where it is analyzed by a series of detectors.

The CPT soil sampler is also convenient for contaminated sites (Figure 24.9). The test consists of pushing a cone penetrometer to the depth where a sample is needed. At the required depth, the cone tip insert is disengaged, the CPT probe is advanced to collect the soil sample while the cone tip stays stationary as in a piston sampler, and then the CPT probe is pulled back to the surface. Such CPT samples are about 40 mm in diameter and up to 400 mm in length.

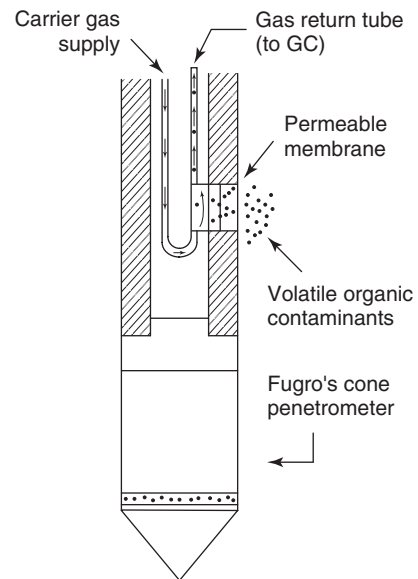


Figure 24.8 MIP CPT gas sampler.

Hydrogeologic data are also very important, as contamination of the groundwater is of great concern to human life. There are two components to these studies. One deals with determining where the groundwater table is and which way the water is flowing (if at all). The other is a determination of the hydraulic conductivity of the soil. Determining the groundwater level is done through the use of monitoring wells and piezometers, as described in section 6.6; in situ hydraulic conductivity measurements are covered in section 7.12.

Finally, the chemical analysis of any soil samples and water samples collected has to be conducted under controlled conditions. This chemical analysis aims at identifying the type and concentration of the chemicals in the ground. The final report should include the geologic data, the soil data, the hydrogeologic data, and the chemical data. It should identify the type of contamination, the extent of the contamination, and the future movement of the contaminants.



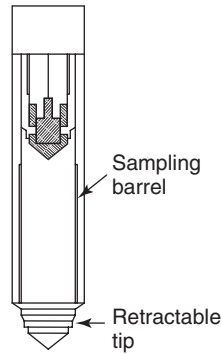


Figure 24.9 CPT soil sampler.

### 24.5.3 Contaminant Transport and Fate

The word *transport* refers to the flow of the contaminant and the word *fate* to the change in form and concentration of the contaminant through chemical reactions. For noncontaminated sites, the steady-state (no influence of time) flow of water through soil is governed by Darcy's law (constitutive law) and conservation of mass (fundamental law). These two equations, combined with boundary conditions and soil properties (hydraulic conductivity), give the solution to steady-state flow problems. This topic was covered in Chapter 13. For transient (influence of time) flow of water through soil, additional equations must be used. Consolidation of saturated layers is an example of transient flow; in that case the additional equation is the one linking the stress applied to the change in volume of the element. This change of volume (settlement) varies with time and adds to the volume of water flowing through the soil. This problem is presented in sections 11.4.6 and 14.14.

For contaminant flow through soil, an additional issue is the movement of the contaminant in terms of concentration. The contaminant may be found in the gas phase, in the liquid phase, or in the solid phase. This movement can take place through transport processes, chemical reaction processes, and biological processes.

#### Transport Processes

*Transport processes* include advection, diffusion, and dispersion.

**Advection.** *Advection* is the movement of the contaminant liquid under a hydraulic gradient. It is the same case as water flow, with Darcy's law and conservation of mass as the equations. One difference is that the seepage velocity  $v_s$  is used rather than the discharge velocity  $v$  (see section 13.2.1) because  $v_s$  represents the actual velocity of the contaminant movement:

$$Q = vA = v_s A_v \quad \text{or} \quad v = nv_s \quad (24.5)$$

where  $Q$  is the flow,  $A$  is the total cross-sectional area,  $A_v$  is the area of the voids, and  $n$  is the soil porosity.

The concentration  $C$  of the contaminant is defined as:

$$C = \frac{M}{V} \quad (24.6)$$

where  $M$  is the mass of contaminant (solute) within the volume  $V$  of the liquid carrying the contaminant (solvent). Associated with the concentration  $C$  is the contaminant mass flux  $F$ , defined as the mass of contaminant passing through a unit area of soil per unit time. The area is the area perpendicular to the flow direction:

$$F_{adv} = \frac{M}{At} = \frac{M}{V} \frac{x}{t} = Cv = nv_s C \quad (24.7)$$

where  $F_{adv}$  is the mass flux of contaminant due to advection (subscript *adv*),  $M$  is the mass of the contaminant,  $A$  is the total cross-sectional area perpendicular to the flow,  $t$  is the increment of time considered, and  $x$  is the distance travelled by the contaminant during  $t$ ; other parameters are defined in Eqs. 24.5 and 24.6. Then the governing differential equation is:

$$\frac{dC}{dt} = -nv_s \frac{dC}{dx} \quad (24.8)$$

**Diffusion.** *Diffusion* refers to the change in concentration of a contaminant due to a chemical gradient. If you put a drop of colored food dye in a glass of water, you will observe diffusion of the dye in the water. This is due to the initial difference in concentration (gradient) of dye between locations in the glass. Another example is the intrusion of seawater into freshwater aquifers (Figure 24.10). This diffusion process is described by Fick's law, which states that the contaminant mass flux is linearly proportional to the change in mass concentration between two points:

$$F_{dif} = -nD^* \frac{dC}{dx} \quad (24.9)$$

where  $F_d$  is the mass flux of contaminant due to diffusion (subscript *dif*),  $n$  is the soil porosity,  $D^*$  is the diffusion



Figure 24.10 Example of diffusion: Seawater intrusion in aquifer. (Copyright © 1995-2013 GEO-SLOPE International Ltd. All Rights Reserved.)

coefficient, and  $dC/dx$  is the concentration gradient. Adolph Fick was a German-born physician who proposed this law in 1855. Remarkably, the value of  $D^*$  does not vary much, with a range of  $1 \times 10^{-9}$  to  $2 \times 10^{-9}$  m<sup>2</sup>/s (Mitchell 1976). Using Fick's law and the equation of continuity gives the governing differential equation:

$$\frac{dC}{dt} = nD^* \frac{d^2C}{dx^2} \quad (24.10)$$

Note that this equation is the same as the governing differential equation for the consolidation theory (Chapter 11, Eq. 11.56), except that  $C$  is replaced by the excess water stress  $u_{we}$  in the consolidating layer and  $nD^*$  is replaced by the coefficient of consolidation  $c_v$ . The solution to this equation for simple boundary conditions was proposed by Crank (1956).

**Dispersion.** Dispersion refers to the fact that the velocity is not the same at all points in the flow field (Figure 24.11). This creates a problem similar to the diffusion component where the concentration  $C$  varies with the distance (longitudinal or transversal), and is written as:

$$F_{dsp} = -nD \frac{dC}{dx} = -n\alpha v_s \frac{dC}{dx} \quad (24.11)$$

where  $F_{dsp}$  is the mass flux of contaminant due to dispersion (subscript dsp),  $n$  is the soil porosity,  $D$  is the dispersion coefficient,  $\alpha$  is the dispersivity,  $v_s$  is the seepage velocity, and  $dC/dx$  is the concentration gradient along the flow. Then the change in concentration with time is given by:

$$\frac{dC}{dt} = n\alpha v_s \frac{d^2C}{dx^2} \quad (24.12)$$

The total mass flux at one point is the sum of the three components. The soil parameters entering into the equations ( $n$ ,  $D^*$ ,  $\alpha$ ) can be measured through laboratory tests. One such test is the column test, in which the contaminant is injected at the top of the column and concentration measurements are made on the effluent at the bottom of the column. The soil parameters can also be obtained from in situ tests where a dye is injected at one location and the dye concentration is checked as a function of time in adjacent monitoring wells.

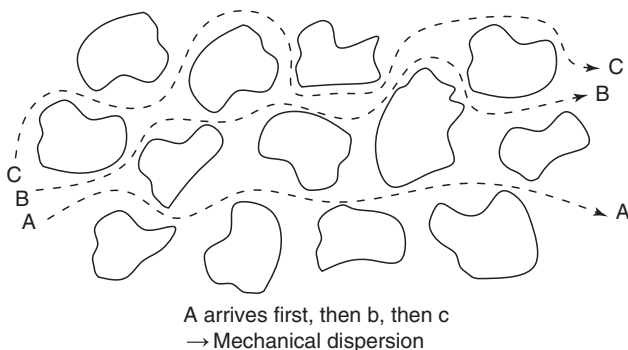


Figure 24.11 Mechanical dispersion.

## Chemical Reaction Processes

Chemical reaction processes include many different types of chemical reactions.

**Sorption and Desorption.** Sorption is the process by which the contaminant becomes attached to the surface of the soil particle. Desorption is the process by which the contaminant gets detached from the surface of the particle. Empirical equations link the mass of contaminant sorbed per unit dry mass of soil  $S$  (e.g., mg/kg or ppm) to the concentration of contaminant in solution at equilibrium  $C$  (e.g., mg/L). Due to sorption, the contaminant velocity  $v_c$  is slower than the seepage velocity  $v_s$ ; in other words, the contaminant movement is slowed down and the water goes faster than the contaminant. A retardation coefficient  $R$  (larger than 1) then links the seepage velocity  $v_s$  to the true contaminant velocity  $v_c$ :

$$v_c = \frac{v_s}{R} \quad (24.13)$$

The retardation coefficient is estimated by laboratory testing or correlation with the ratio  $S/C$ .

**Precipitation and Dissolution.** Precipitation and dissolution reactions involve the level of solubility of a contaminant in the carrier liquid (most often water). The degree of solubility varies from one contaminant to the next and is characterized by an equilibrium constant  $K$ , which is high for high solubility and vice versa. Sulfate salts and chlorides tend to be highly soluble, sulfide and hydroxides tend to be least soluble, and carbonates and silicates have intermediate solubility.

**Oxidation and Reduction.** These reactions are often called redox reactions. Oxidation is a loss of electrons. Reduction is a gain of electrons. Redox reactions are characterized by the redox potential  $E_h$  expressed in volts. The redox potential is a measure of the affinity of a substance for electrons (its electronegativity). The reference potential is that of hydrogen, which is set at 0 volt. Substances more strongly electronegative than hydrogen have positive redox potentials. These are substances that are capable of oxidizing; for example, oxygen has a redox potential of 1.23 V. In contrast, substances less strongly electronegative than hydrogen have negative redox potentials and are capable of reducing; for example, calcium has a redox potential of  $-2.87$  V. Hydrogen peroxide is a powerful oxidant that is used in low concentrations to treat wounds because it releases oxygen, which kills bacteria.

**Acid-Base Reactions.** An acid-base reaction is a gain or loss of a proton ( $H^+$ ) or the gain or loss of a hydroxyl group ( $OH^-$ ). An acid is a proton donor, and a base is a proton taker. These reactions affect the pH of the soil and the groundwater and therefore the type of remediation strategy.

**Other Reactions.** Other reactions include complexation, ion exchange, hydrolysis, and volatilization. Complexation takes place when organic or inorganic ions or molecules combine in the dissolved phase. Ion exchange occurs when

an ion is replaced by another one. This type of reaction, called *isomorphous substitution*, can take place at the surface of clay particles, with, for example, a  $\text{Ca}^{++}$  taking the place of an  $\text{Na}^+$ . *Hydrolysis* is the reaction between an organic molecule and water. *Volatilization* refers to the transformation of a liquid or solid into gas; it applies to volatile organics, for example, and is governed by Henry's law:

$$C_a = K_H C_w \quad (24.14)$$

where  $C_a$  is the concentration of the contaminant in the gas phase,  $K_H$  is Henry's constant for that contaminant, and  $C_w$  is the concentration of the contaminant in the liquid phase. William Henry was a British chemist who proposed this law in 1803. Henry's constant and many other constants associated with chemical reactions for typical contaminants in soils can be found in EPA publications such as *Subsurface Contamination Reference Guide* (U.S. EPA 1991) or in reference books such as Sharma and Reddy (2004).

### Biodegradation

*Biodegradation* is a redox reaction mediated by microorganisms; it can be aerobic or anaerobic. Aerobic biodegradation takes place in the presence of oxygen, which acts as an electron acceptor from the substance; anaerobic biodegradation takes place in the absence of oxygen. Some microorganisms naturally occurring in soil have the remarkable ability to degrade and transform many compounds, including hydrocarbons, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), pharmaceutical substances, radionuclides, and metals. However, for degradation to take place, the microorganism must be matched to the contaminant to be degraded. The microorganisms facilitate the transfer of electrons from a donor to an acceptor and in the process transform the substance to which it is attached. Typical outputs of biodegradation are methane, carbon dioxide, and water.

### Governing Differential Equation

The governing differential equation (GDE) can be obtained by adding the contributions from the previously discussed processes. In the simple case of a one-dimensional flow, the total mass of contaminant per unit volume of soil  $C_T$  is:

$$C_T = \rho_d C_s + \theta_w C_w + \theta_g C_g \quad (24.15)$$

where  $\rho_d$  is the dry density of the soil (mass of dry soil over volume of soil),  $C_s$  is the concentration of contaminant in the solid phase (mass of contaminant over mass of solids),  $\theta_w$  is the volumetric water content (volume of water over volume of soil),  $C_w$  is the concentration of contaminant in the liquid phase (mass of contaminant over volume of water),  $\theta_g$  is the volumetric gas content (volume of air over volume of soil), and  $C_g$  is the concentration of contaminant in the gas phase (mass of contaminant over volume of air). For a saturated

flow,  $\theta_g$  is zero,  $\theta_w$  is equal to the porosity  $n$ , and Eq. 24.15 becomes:

$$C_T = \rho_d C_s + n C_w \quad (24.16)$$

The contaminant mass flux  $F_{adv}$  (mass of contaminant crossing a unit area of soil per unit time; see Eq. 24.7) due to water flow or advection is given by:

$$F_{adv} = C_w n v_s \quad (24.17)$$

where  $n$  is the soil porosity and  $v_s$  is the seepage velocity. The contaminant mass flux  $F_{dif}$  (mass of contaminant crossing a unit area of soil per unit time; see Eq. 24.9) due to diffusion is given by:

$$F_{dif} = -D^* n \frac{dC_w}{dx} \quad (24.18)$$

where  $D^*$  is the effective diffusion coefficient,  $n$  is the porosity, and  $x$  is the coordinate along the travel direction of the water.

The contaminant mass flux  $F_{dsp}$  (mass of contaminant crossing a unit area of soil per unit time; see Eq. 24.11) due to dispersion is given by:

$$F_{dsp} = -D_L n \frac{dC_w}{dx} = -\alpha_L v_s n \frac{dC_w}{dx} \quad (24.19)$$

where  $D_L$  is the dispersion coefficient in the longitudinal direction,  $n$  is the porosity,  $dx$  is the increment of  $x$ , and  $\alpha_L$  is the longitudinal dispersivity.

If we combine the transport from advection, diffusion, and dispersion, we obtain, for saturated flow:

$$\begin{aligned} F_T &= F_{adv} + F_{dif} + F_{dsp} \\ &= n v_s C_w - D^* n \frac{dC_w}{dx} - \alpha_L v_s n \frac{dC_w}{dx} \end{aligned} \quad (24.20)$$

Then we write that for conservation of mass, the change in concentration of mass of contaminant with time has to be equal to the slope of the curve describing the flux vs. distance along the flow path:

$$\frac{dC_T}{dt} = -\frac{dF_T}{dx} \quad (24.21)$$

This leads to:

$$\begin{aligned} &\frac{\partial(\rho_d C_s)}{\partial t} + \frac{\partial(n C_w)}{\partial t} \\ &= -\frac{\partial}{\partial x} \left( n v_s C_w - (D^* n + \alpha_L v_s n) \frac{\partial C_w}{\partial x} \right) \pm S \end{aligned} \quad (24.22)$$

The term  $S$  is added to include any sources or sinks of contaminants, such as those due to chemical reactions. The partition coefficient  $K_d$  is defined as:

$$K_d = \frac{C_s}{C_w} \quad (24.23)$$

If we ignore sources and sinks, we get the equation:

$$\frac{\partial C_w}{\partial t} = -\frac{v_s}{\left(\frac{\rho_d K_d + n}{n}\right)} \frac{\partial C_w}{\partial x} + \frac{(D^* + \alpha_L v_s)}{\left(\frac{\rho_d K_d + n}{n}\right)} \frac{\partial^2 C_w}{\partial x^2} \quad (24.24)$$

After setting  $R_d$ , the retardation factor, and  $D_H$ , the hydrodynamic dispersion as:

$$R_d = \frac{\rho_d K_d + n}{n} = 1 + \frac{\rho_d K_d}{n} \quad (24.25)$$

$$D_H = D^* + \alpha_L v_s \quad (24.26)$$

Then the GDE for contaminant transport for this simplified case is:

$$\frac{\partial C_w}{\partial t} = -\frac{v_s}{R_d} \frac{\partial C_w}{\partial x} + \frac{D_H}{R_d} \frac{\partial^2 C_w}{\partial x^2} \quad (24.27)$$

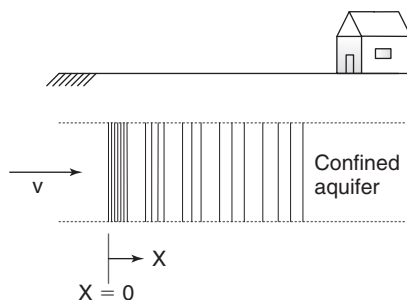
Before we can solve this equation, we have to define the boundary conditions and the initial conditions. Let's take the simple case in which the water is flowing horizontally in a confined aquifer with a point source of contamination that remains constant versus time (Figure 24.12). In this case the boundary conditions and initial conditions are:

$$\begin{aligned} C_0 &= \text{constant contaminant concentration at point} \\ x = 0 \text{ and } t = 0 \end{aligned} \quad (24.28)$$

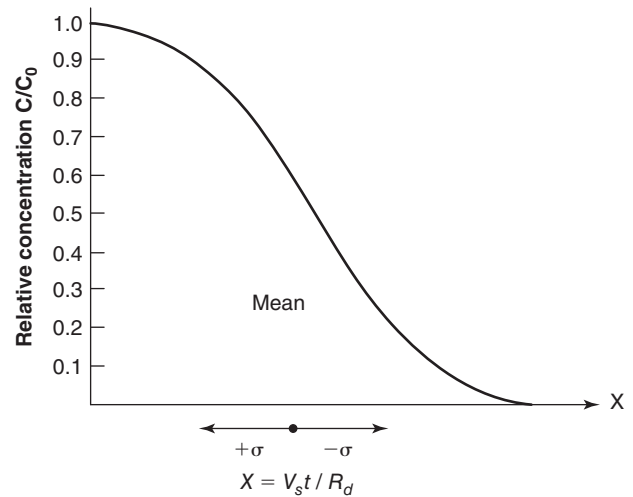
The solution was presented by Fetter (1992):

$$C_w(x, t) = \frac{C_0}{2} \operatorname{erfc} \left( \frac{R_d x - v_s t}{\sqrt{4 R_d D_H t}} \right) \quad (24.29)$$

where  $\operatorname{erfc}$  is the complementary error function. Propagation of the contamination is shown as normalized concentration ( $C/C_0$ ) versus lateral extent  $x = v_s t / R_d$  in Figure 24.13. Solutions for one-dimensional flow and more complicated boundary conditions can be found in Hemond and Fechner-Levy (2000). For two-dimensional and three-dimensional conditions, the GDE can be solved by the finite difference method or other numerical schemes.



**Figure 24.12** One-dimensional transport in a confined aquifer.



**The profile of a diffusing front as predicted by the complementary error function**

**Figure 24.13** Diffusing front for one-dimensional contaminant transport. (After C. W. Fetter, *Contaminant Hydrogeology*, New York: Macmillan Publishing Company, 1992)

## 24.6 REMEDIATION

Remediation of contamination is the action of reducing the risk of detrimental effect on human life to an acceptable level. Once the type and extent of contamination have been identified, there are three common options: monitoring, containment, and remediation. Let's look first at risk assessment, as it influences the choice of remedial measure.

### 24.6.1 Risk Assessment and Strategy

*Risk* is the product of the probability of an event happening or being exceeded times the value of the consequence. The value of the consequence and therefore the risk can be expressed in cost units, in human or animal fatalities, or in number of people sick (among others). Acceptable risk is then established by considering the risk associated with normal life activities and accepting such levels as targets for contamination. In the United States, there are two risk assessment techniques: one general technique from the EPA and one technique for leaking petroleum tanks from ASTM.

#### *EPA Procedure*

The EPA procedure (U.S. EPA 2001) advances in four steps: data collection and evaluation, exposure assessment, toxicity assessment, and risk characterization. *Data collection* consists of identifying the contaminants, their concentration, the source of the contamination, and the soil in which the contaminant may propagate. *Exposure* is defined as the contact of a chemical or biological agent with the outer boundary of a human being. The amount of exposure is measured by the extent of contact with that outer boundary during a specified amount of time. Exposure assessment

includes determining the exposure setting (e.g., weather, topography, geology, hydrogeology), the exposure pathways (e.g., likely transport routes, speed of propagation, proximity of human activities), and the exposure concentrations (e.g., current and future chemical concentration).

*Toxicity* is the adverse effect of a contaminant on human life (e.g., cancer, birth defect). Toxicity assessment includes determining if the chemical is a carcinogen or noncarcinogen. The toxicity of noncarcinogenic chemicals is quantified by the reference dose (RfD in mg/kg/day), which is the daily dose that would not create an appreciable risk of deleterious health effects during a lifetime. The toxicity of carcinogenic chemicals is quantified by the slope factor (SF in (mg/kg/day)<sup>-1</sup>) that is the upper bound (95% confidence) on the increased cancer risk from a lifetime exposure to the chemical. The EPA publishes tables of RfDs and SFs for many chemicals (Sharma and Reddy 2004). The *risk* quantification is done by using the hazard quotient *HQ* for noncarcinogens and the risk *R* for carcinogens, as follows:

$$HQ = \frac{E}{RfD} \quad (24.30)$$

$$R = CDI \times SF \quad (24.31)$$

where *E* is the chemical intake (mg/kg/day) and *CDI* is the chronic daily intake averaged over 70 years (mg/kg/day). The EPA considers a value of *HQ* higher than 1 and *R* larger than 10<sup>-6</sup> to be unacceptable.

### ASTM Procedure

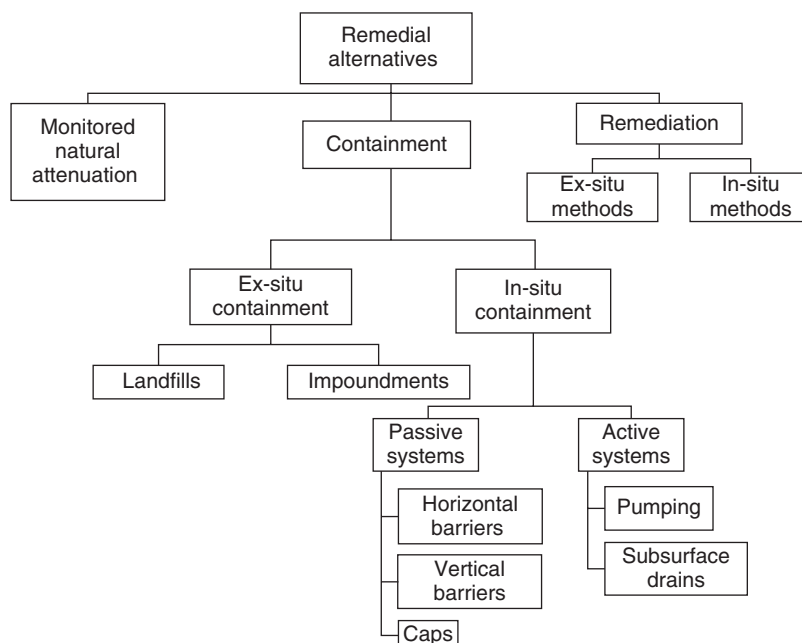
The ASTM procedure (ASTM 1995) is aimed at the remediation of sites with leaking petroleum tanks, where the chemical contaminants may include benzene, toluene, and xylene, for example. It proceeds in three “tiers” or steps.

Tier 1, much like the EPA method, consists of collecting data, including the concentration of chemicals. These concentrations are then compared with risk-based screening levels (RBSLs) found in published tables. If the levels are below the RBSL for the most severe contamination propagation pathway, no action is required. If not, remediation can be planned to meet the tier 1 RBSL, or a more sophisticated Tier 2 analysis of the problem can be chosen.

In Tier 2, the points of compliance are selected and the site-specific target levels (SSTLs) are determined. Additional soil and water data are collected and simple calculations are made to predict the transport and fate of the chemical over time. If the STSL is met, no further action is necessary. If not, remediation to meet the STSL is undertaken, or a more refined Tier 3 evaluation takes place.

Tier 3 evaluation makes use of analyses more sophisticated than Tier 2 analyses and remediation takes place if the levels obtained after the Tier 3 analysis do not meet the target levels.

The general strategy, once the type and extent of contamination have been identified, is to choose among the following three common options: monitoring, containment, or remediation (Figure 24.14). Monitoring is selected if the



**Figure 24.14** Remediation alternatives and decision tree. (After Sharma and Reddy, 2004. This material is reproduced with permission of John Wiley & Sons, Inc.).

level of contamination is minor and the risk is low; containment is most often a temporary measure; and remediation of soil and water is the long-term alternative.

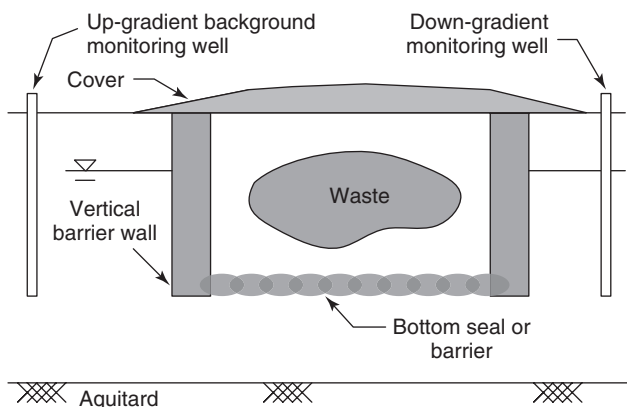
### 24.6.2 In Situ Waste Containment

In situ waste containment is typically used as a temporary measure to prevent further propagation of the contaminant while a more permanent remediation solution is set up. Containment is sometimes used as a permanent measure if the cost of cleanup technologies is prohibitive or the technologies are impractical. Two types of systems exist: passive systems and active systems. Passive systems are barriers to enclose the waste and minimize spreading (vertical barriers, bottom barriers, or surface covers), whereas active systems are generally pumping wells and drains.

#### Vertical Barriers

*Vertical barriers* (Figure 24.15) are built to surround the waste. They are built from the surface down to a naturally impervious soil layer. They can be hanging barriers above an impervious layer if the contaminant will not propagate with depth, as in the case of LNAPLs that float on the water table. There are several types of vertical barriers: slurry trench barriers, grouted barriers, and steel sheet pile barriers.

**Slurry Trench Barriers.** Slurry trench barriers are the most common type of vertical barrier. They are constructed by excavating a narrow trench about 0.5 to 1 m wide to the depth required. During the excavation, the trench is filled with a liquid slurry made of water and bentonite clay (about 5% bentonite by weight). The role of the bentonite slurry is to seal the walls of the trench and provide a horizontal pressure that minimizes the chance of trench wall collapse. The slurry, which is at least 3% heavier than water, is kept level with the top of the trench, and is therefore higher than the water level in the soil. As a result, the slurry permeates out through the trench wall and deposits a film of very fine bentonite clay particles on the wall. This very low permeability film



**Figure 24.15** Vertical, bottom, and surface containment barriers. (After Sharma and Reddy, 2004. This material is reproduced with permission of John Wiley & Sons, Inc.).

can be 10 mm thick or more and seals the wall against water penetration in the trench.

When the trench is completed and full of slurry, the trench is backfilled with low-permeability backfill. This backfill may be a soil-bentonite mix (SB), or a cement-bentonite mix (CB), or it can involve a geomembrane. Soil-bentonite barrier backfill is typically a mixture of sand (excavated soil if possible), dry bentonite, and bentonite slurry. It has the consistency of wet concrete with 25 to 50% fines but no gravel. This low-permeability backfill is placed at the end of the slurry trench and displaces the slurry forward toward the ongoing excavation. The target hydraulic conductivity of the trench is  $10^{-9}$  to  $10^{-10}$  m/s. Cement-bentonite barrier backfill is similar to SB backfill except that the soil is replaced by cement. A typical mix would be 5% bentonite, 15% cement, and 80% water. CB barriers are stronger than SB barriers, but have lower permeability because the cement hinders the full expansion of the bentonite. Geomembrane barriers are installed by lowering a membrane into the open hole so that it seals the bottom and the side walls of the trench. Installation of a geomembrane can be a complex and difficult operation, but the permeability of the membrane is much lower than that of the other two systems.

One important aspect of slurry trench barriers is the design for stability of the trench. An earth pressure analysis must be conducted to calculate the global factor of safety against collapse of the trench wall when the trench is fully excavated. Such design is rooted in the content discussed in Chapter 22.

**Grouted Barriers.** Grouted barriers are prepared first by rotary drilling and then by grout injection. A column is constructed, then another one in line with the first one, and then another one in line with the first two, and so on in sequence so that in the end a wall of columns forms the barrier. Typically a first set of columns is built by skipping the intermediate columns, and then the intermediate columns are built when the first set of columns has hardened. Pressure grouting, jet grouting, and soil mixing are the techniques most commonly used. *Pressure grouting* consists of injecting grout under some pressure after a hole is drilled with diameters in the range of 1 to 1.5 m. The injection is done by the point injection technique or by the “tube a manchette” technique. *Jet grouting* consists of drilling a small hole and then rotating the drill rod upon withdrawal while jetting grout laterally under pressure to enlarge the hole. The pressure of the jet is in the range of 35 to 40 MPa. Grouted columns created with this technique can reach 3 m in diameter. *Soil mixing* consists of literally mixing the soil with grout (e.g., 20% by weight) as drilling takes place. In other words, the drilling mud is replaced by the soil-grout mixture. This minimizes the amount of cuttings generated. With grouted columns as barriers, it is very important to ensure overlapping of the columns to achieve a good seal against contaminant flow.

**Steel Sheet Pile Barriers.** To create a steel sheet pile barrier, steel sheet piles are driven one beside the other to

**Table 24.3 Advantages and Drawbacks of Waste Containment Systems**

System	Advantages	Drawbacks
Slurry barriers	Long-term, inexpensive, no maintenance required, well proven, available materials	Compatibility between slurry and contaminant; need for natural impervious layer; problems with boulders, caverns
Grout barriers	Injection of grout only requires small holes, can go very large depth, can fill caverns, can vary setting time	Difficult when soil is not pervious; holes and gaps more likely to jeopardize containment of liquids
Geomembrane barriers	Effective, compatible with many contaminants	Sealing between sheets is complex process; keying membrane in bottom layer is complex as well; expensive
Steel sheet pile barriers	No excavation needed, no maintenance required	Seal between sheet piles is not effective; corrosion problems; iron not compatible with many contaminants
Pumping	Less costly than barrier, design flexibility, control of pumping rates, common technology, depth not a problem	Requires frequent monitoring to limit propagation; maintenance required; capture zone limited
Subsurface drains	Economical to operate, drain location flexible, fairly reliable, simple and economical construction	Not for low-permeability soils; underdrains tough to place; monitoring required; not for deep contamination; potential clogging; excavation required

(After Sharma and Reddy 2004.)

form a barrier in the soil. The advantages of this technique are that no excavation is necessary and the barrier installation is rapid. One problem is the corrosion issue and the lack of a good seal across the joints between sheet piles.

Table 24.3 (after Sharma and Reddy 2004) summarizes the advantages and drawbacks of the various barrier techniques.

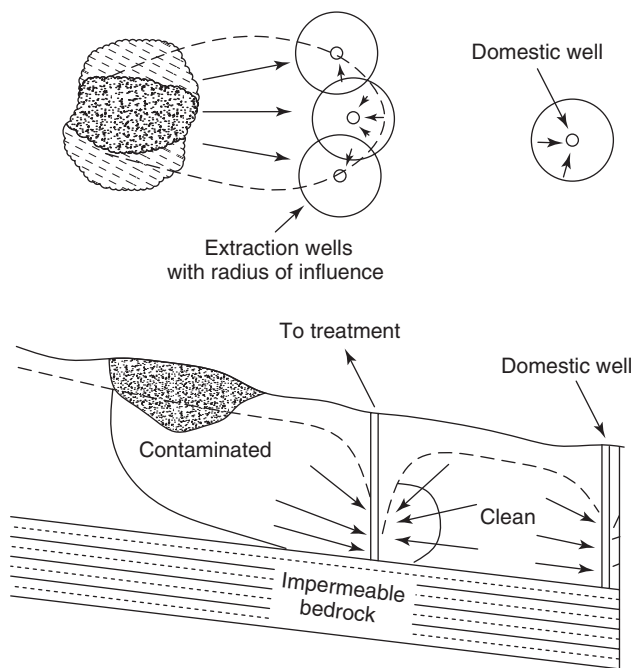
### **Bottom Barriers**

Bottom barriers (Figure 24.15) are built to seal the bottom of a contaminated zone. This may be necessary when there is no natural low-permeability layer under the contaminated zone and the contaminant can propagate downward. A bottom barrier can be constructed by grouting or directional drilling. Grouting may be done by pressure grouting or jet grouting, but in both cases the injection pipe is driven or vibrodriven to the depth of the bottom barrier and a grout bulb is constructed. The operation is repeated until the overlapping bulbs form a bottom barrier. The drawback of this technique is that holes have to be punched through the waste or contaminated zone. Directional drilling can be used to reduce this problem: It consists of setting an inclined drill outside of the contaminated zone and reaching underneath that zone by drilling at an angle. Then the hole is grouted. Side-by-side holes are drilled and grouted to form the bottom barrier.

*Surface covers* (Figure 24.15) are built to cap the contaminated zone. They prevent the infiltration of running water and rain, thereby minimizing leaching; they prevent atmospheric

contamination, reduce erosion, and improve aesthetics at the site. They are typically made of multiple layers, each with a specific purpose. The base layer or foundation layer creates a uniform surface on which to build other layers. Above that is the gas collection layer, made of coarse-grained soil and equipped with venting pipes. Above that is the barrier layer, made of compacted clay and a geomembrane or a geosynthetic clay liner (see Chapter 25) to prevent the surface water from entering the contaminated zone. This layer typically has a hydraulic conductivity of  $10^{-9}$  m/s or less. Above that is the drainage layer, made of coarse-grained soil and /or geotextile to collect any water percolating down through the top layers. Above that is the surface and protection layer, made of topsoil and erosion control geosynthetic to prevent erosion and foster plant growth.

*Pumping wells* (Figure 24.16) are built to pump contaminated water out of the soil or introduce a hydraulic gradient that will force the plume to move in the desired direction. These wells are used when the contaminant is mixed into the water (soluble). Injection wells can be used at some distance from pumping wells to force the liquid to go toward the pumping wells. This strategy can be used when the contaminant is a liquid not miscible with water. Pumping and injection are most effective when the soil is coarse grained with high permeability. In the design of the well, the following issues must be addressed: depth, spacing, zone of influence, pumping rate, and number of wells. The treatment of the effluent must be addressed through an on-site or off-site treatment.



**Figure 24.16** Pumping wells. (After Sharma and Reddy, 2004. This material is reproduced with permission of John Wiley & Sons, Inc.).

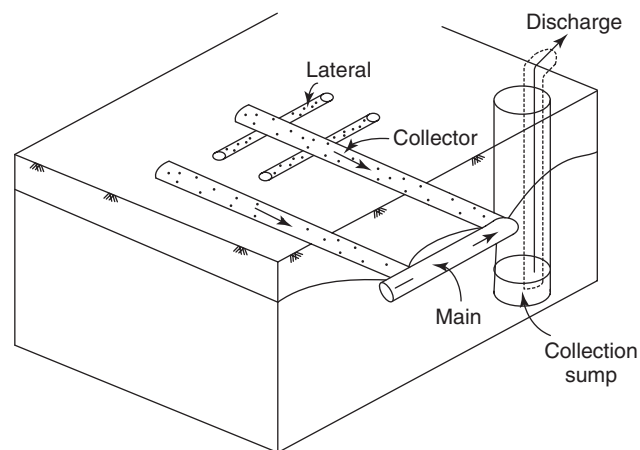
*Subsurface drains* (Figure 24.17) play essentially the same role as pumping wells, but they drain the contaminated zone by gravity instead of pumps. Drains have the advantages of being a more economical solution than pumping, and they can be used in low-permeability soils where pumping is not efficient. Drains can be placed horizontally as perforated pipes, or vertically as draining boreholes with a sump pump, or a combination of both. As in the case of pumping, the issues to be addressed are the location of the drains to take best advantage of gravity forces, depth, spacing, and zone of influence. Other issues specific to drains include pipe diameter, gradient of the slope, filters to prevent clogging, and size of the sump and pump.

### 24.6.3 Soil Remediation

The most commonly used methods of soil remediation are soil vapor extraction, soil washing, and solidification. However, many other techniques are available.

#### *Soil Vapor Extraction*

*Soil vapor extraction* (SVE), also called *soil venting*, *vacuum extraction*, and *aeration*, consists of sucking the contaminated air out of the voids in the unsaturated soil zone above the water table. It is applied mostly to the volatile organic compounds (VOCs) that form in petroleum-contaminated soils. Extraction wells are installed on a grid, the vapor is removed by the vacuum gradient, and the collected vapor is treated using carbon filters, for example. The best candidates for such treatment are soils that are highly permeable and



**Figure 24.17** Subsurface drains. (After Sharma and Reddy, 2004. This material is reproduced with permission of John Wiley & Sons, Inc.).

gasses that have a vapor pressure larger than 70 Pa and a Henry's law constant higher than 0.01.

#### *Soil Washing*

*Soil washing* (SW) consists of excavating the soil from the site and treating it on site with a soil scrubbing system. A chemically suitable washing fluid is selected on the basis of the contaminants to be removed. After excavation, the soil is washed by forcing it through an energetic scrubbing system where it is mixed with the washing fluid. The coarse fraction is usually easier to clean than the fine fraction, because of the size and chemical complexity of clay particles. The clean soil is returned to its initial location; the remaining contaminated soil and the contaminated effluent are sent elsewhere for further treatment or disposal. This technique becomes economically attractive when the amount of soil to be treated is large (say, more than 50 MN).

#### *Stabilization and Solidification*

*Stabilization and solidification* (S/S), also called *immobilization* or *fixation*, consists of treating the contaminant in such a way that it is bound to the soil particles and remains trapped at the site. The method can be done ex situ or in situ. For the ex situ method, the contaminated soil is excavated and mixed with a stabilizing agent that fixes the contaminant to the soil particles. The mix is cured, and then the stabilized soil is replaced at the site or disposed of in a landfill. For the in situ method, the stabilizing agent is injected or mixed with the in situ contaminated soil to prevent the contaminants from moving away from the site. Portland cement is an example of a stabilizing agent.

#### *Electrokinetic Remediation*

*Electrokinetic* (EK) remediation consists of applying a potential difference between two electrodes (e.g., steel bars) driven



into the contaminated soil. The potential difference (say, 40 V/m) drives the contaminated fluid to the electrodes where it is collected and removed. The anode is positively charged and attracts negatively charged contaminants (anions); the cathode is negatively charged and attracts positively charged contaminants (cations). The flow rate ( $\text{m}^3/\text{s}$ ) generated by EK remediation is proportional to the electrical potential between electrodes and the dielectric constant of the soil, but inversely proportional to the distance between electrodes and the viscosity of the fluid. EK remediation works well in fine-grained soils, which are otherwise difficult to clean.

### **Thermal Desorption**

*Thermal desorption* (TD) consists of heating the contaminated soil to temperatures between 100 and 500°C. These high temperatures vaporize the contaminants, which are then removed by a vapor extraction system. This method works for volatile and semivolatile organic compounds, but not for metals. Note that the contaminants are not destroyed as they would be during incineration (much higher temperature). TD can be performed in situ or ex situ. For ex situ treatment, the soil is excavated, brought to the treatment plant, and subjected to the heating process. In situ, heating blankets are placed on the surface for shallow treatment and heating wells are installed for deeper zones. If the water content is too high (e.g., more than 15%), dewatering may be necessary as a first step.

### **Vitrification**

*Vitrification* (VT) consists of melting the contaminated soil into glass. This requires a lot of heat, with temperatures of about 1800°C. At such a temperature, organics are either destroyed or vaporized and stable inorganic compounds are surrounded by the molten soil. Upon cooling, the mass turns to glass and the inorganic contaminants are fixed in place. The method can be applied in situ or ex situ. In situ electrodes are placed and very high voltage and very high current are applied (e.g., 4000 V, 4000 A) with a power requirement of 3 to 4 MW. Gas collection hoods are placed on top of the electrodes to evacuate the gasses created to a treatment system.

### **Bioremediation**

*Bioremediation* (BR) involves microorganisms or microbes eating the contaminant, transforming it into nontoxic by-products through their digestive systems, and releasing those by-products to the atmosphere. The by-products are usually carbon dioxide and water or organic acids and methane. Appropriate microorganisms are found naturally in the soil and include yeast, fungi, and bacteria. The best contaminant food for them is petroleum hydrocarbons; other organic contaminants and inorganic contaminants are not as well suited to bioremediation. Microorganisms operate best in the presence of moisture, nutrients, and oxygen, so *biostimulation* consists of providing them with those three components to enhance the

transformation process. *Bioaugmentation* consists of adding selected microorganisms to degrade a specific contaminant or supplement the work of the indigenous microorganisms.

Bioremediation may be aerobic (with oxygen) or anaerobic (without oxygen), but the aerobic process takes less time and is favored. Both in situ and ex situ treatment are possible. Either way, monitoring (e.g., for  $\text{CO}_2$  and  $\text{O}_2$ ) is necessary to adjust the stimulation process when appropriate. When stimulation involves providing more oxygen, it can be done in the form of bioventing (bringing air into the soil) or injection of hydrogen peroxide.

### **Phytoremediation**

*Phytoremediation* (PR), from the word *phyto* in Greek which means “plant,” is the natural soil remediation work done by plants through their root systems. The contaminant crosses the root membrane to enter the plant, which either degrades the contaminant or stores it in the plant tissue. Phytoremediation is best suited for sites with low levels of contamination at shallow depth (less than 3 m). It represents a final cleanup strategy rather than a main remediation method.

Table 24.4 summarizes the advantages and drawbacks of soil remediation methods.

#### **24.6.4 Groundwater Remediation**

Groundwater is a very important resource to humankind. It represents 40% of our drinking water and must be kept free of contaminants. Groundwater remediation includes several different methods: pump and treat, in situ flushing, permeable reactive barriers, in situ air sparging, monitored natural attenuation, and bioremediation.

#### **Pump and Treat**

The pump and treat (PT) technique consists of installing a well from which the water is pumped out of the contaminated soil, treating the contaminated water, and pumping the water back into the soil or to another appropriate location (Figure 24.18). A typical configuration is to have a row of pumping wells downstream of the contaminant flow and a series of recharging wells upstream of the contaminant flow. That way the pumping wells can also serve as monitoring wells for the efficiency of the treatment. The zone of influence and the depth of the wells, as well as the pumping rate, are part of the design.

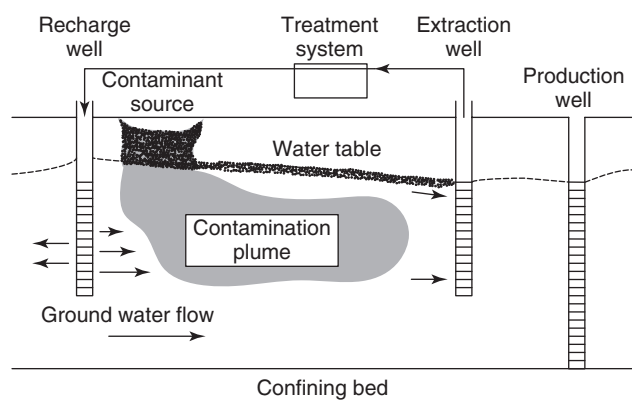
#### **In Situ Flushing**

In situ flushing (ISF) consists of setting up the same kind of wells as in the pump and treat solution, but in this case the cleaning liquid is injected through the upstream wells, passes through the contaminated soil, cleans it, and is pumped out at the downstream wells. The cleaning liquid is carefully selected to remove the contaminant from the water without hurting the environment. The difference between PT and ISF is that with ISF, the cleaning is done in the soil rather than outside the soil as with PT.

**Table 24.4 Advantages and Drawbacks of Soil Remediation Methods**

Method	Advantages	Drawbacks
Soil vapor extraction	Easy installation, low disturbance, short time, economical	Not possible in low permeability areas; need air emission permits; only for unsaturated soils
Soil washing	Reduces volume of contaminated soil, excavation and efficient treatment on site, few permits required	Ineffective for soils with high fine content; relatively expensive; public exposure possible
Stabilization/solidification	Low cost, widely applicable, simple, high throughput rates	Contaminants remain; increased volume; volatiles created; limits future use
Electrokinetic remediation	Applicable to fine-grained soils, wide range of contaminants, less expensive	Changes pH; buried metal is a problem; stagnant zones between electrodes
Thermal desorption	Very rapid treatment, readily available equipment, very good for volatile organics	Dewatering may be necessary; not good for fine-grained soils; not usable for heavy metals; large space required
Vitrification	Long-term durability, wide applicability, reduction of volume, public acceptance, cost-effective for difficult sites	Difficult for very wet soils; limited depth (<7 m); not possible if >10% organics; high energy cost; dangerous in some cases
Bioremediation	Very good for organic contaminants, minimum equipment required, no excavation, low cost	Highly sensitive to local conditions; monitoring required; long treatment time
Phytoremediation	Less expensive, safe, in-place treatment	Shallow treatment (<7 m); slow; still experimental; potential contamination of food chain

(After Sharma and Reddy 2004.)



**Figure 24.18** Pump and treat setup. (After Sharma and Reddy, 2004. This material is reproduced with permission of John Wiley & Sons, Inc.).

### Permeable Reactive Barriers

Permeable reactive barriers (PRBs) are treatment walls placed in the soil; they let the water go through but not the contaminants, which are immobilized or degraded as the groundwater flows through the barrier. Typically a trench is built and filled with a carefully selected reactive agent. As the contaminated water flows through the PRB, the clean water comes out and the contaminant is transformed into nontoxic by-products.

### In Situ Air Sparging

In situ air sparging (ISAS) consists of drilling injections wells through the contaminated soil to reach underneath the plume and injecting compressed air under the contaminated plume. Because it is lighter, the air flows upward through the contaminated water, entrains contaminants vapors which are then evacuated through soil vapor extraction. As a positive side effect and in the process the air brings oxygen which enhances the activity of microorganisms and bioremediation. ISAS is best suited to high permeability soils ( $k > 10^{-5}$  m/s) and to the decontamination of volatile organic compounds, as in the case of leaking underground petroleum storage tanks.

### Monitored Natural Attenuation

Monitored natural attenuation (MNA) is the “do nothing and monitor” or “watch and wait” solution. It consists of monitoring the process of natural remediation, including natural bioremediation, dilution, dispersion, and volatilization. There is no human intervention in this decontamination process.

### Bioremediation

Bioremediation (BR) for contaminated groundwater works according to the same principles as bioremediation for contaminated soil. It is different from MNA in that there is human intervention to optimize the digestive process of the microorganisms that eat the contaminant. This intervention

includes the injection of oxygen and nutrients in the water (biostimulation) or the injection of additional microorganisms (bioaugmentation). BR works best with low hydraulic gradients and permeable soils ( $k > 10^{-6}$  m/s).

## 24.7 LANDFILLS

Most landfills (Figures 24.19 and 24.20) are used as permanent repositories of municipal solid waste, which is the main topic of this section. In the United States, each person generates about 20 N (1 N is the weight of a small apple) of MSW per day (20 N/person/day). This number used to be 12 N in 1960, reached 20 N in 1990, and has stabilized since then, but the population continues to grow, so landfills have to handle more and more MSW. The total amount of MSW per year in the United States is close to 2.5 million MN per year. The best ways to reduce waste, in order of preference, are:

1. Source reduction
2. Recycling and/or composting
3. Disposal in combustion facilities and landfills

Although the amount of waste being recycled has increased 10-fold over the past 40 years, today more than 50% of all MSW still ends up in a landfill. It is extremely important that these landfills be designed to keep the waste

from contaminating soil and water and burdening future generations with unwanted problems.

### 24.7.1 Waste Properties

As mentioned in section 24.2 and Figure 24.2, municipal solid waste in landfills consists primarily of paper, plastic, and food scraps. However, you can also find the odd rusted refrigerator and car tires. It is difficult to come up with the friction angle or modulus of elasticity of an old fridge or a car tire, yet these are the type of properties we are accustomed to using. To complicate matters further, the waste can be in various stages of decomposition, which affect its engineering properties. The only way to answer this problem is by testing the site-specific waste at a large-enough scale. This has been the effort of many researchers and engineers, including Landva and his colleagues (Landva and Clark 1990). The following values are given to provide an order of magnitude of such properties, but the best approach consists of obtaining site-specific values of these parameters through testing at large scale—a scale large enough to be representative of the MSW behavior.

The *unit weight*  $\gamma$  of MSW has been measured in large pits and reported by many authors. The first observation is that  $\gamma$  is highly variable depending on the type of waste, the degree of compaction, the state of decomposition, the proportion of daily soil cover, and the depth of the landfill.

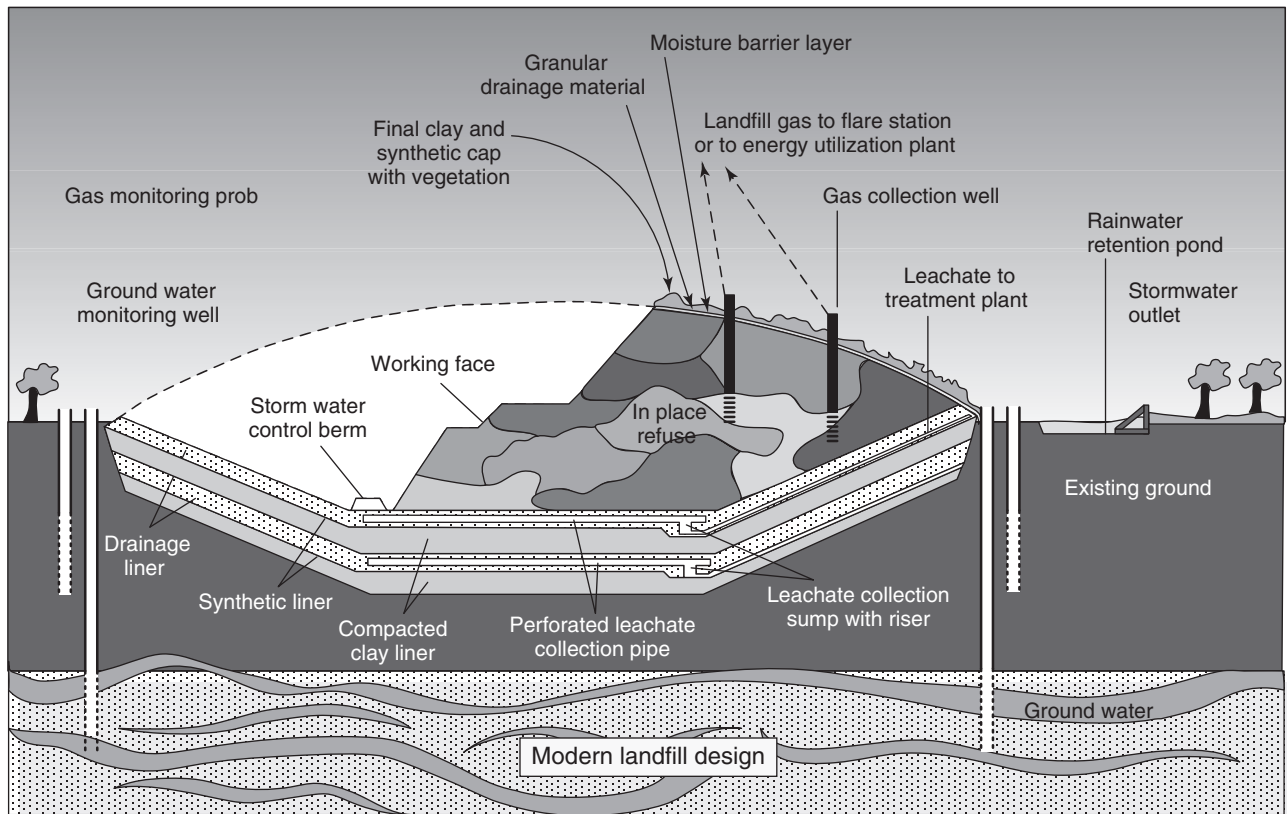


Figure 24.19 Cross section of a landfill



**Figure 24.20** Landfill under operation. (Photo provided courtesy of the Texas Comptroller of Public Accounts from the Energy Report 2008, available at <http://www.window.state.tx.us/specialrpt/energy/>)

Numbers ranging from 3 to 14 kN/m<sup>3</sup> have been reported, with an average of 8 kN/m<sup>3</sup>. The unit weight increases and the variability decreases as depth increases in the waste increases. Porosity is reported to vary between 0.4 and 0.6, void ratio between 0.67 and 1.5, and water content between 0.15 and 0.4 (Sharma and Reddy 2004). Field permeability measured in MSW pits gave a range of 10<sup>-5</sup> to 4 × 10<sup>-3</sup> m/s (Landva and Clark 1990). Shear strength data collected by many authors was reviewed by Kavazanjian (1999), who proposed a bilinear lower-bound envelope. The first part applies to normal stresses lower than 30 kPa and gives  $c = 24$  kPa and  $\phi = 0$ . The second part applies to normal stresses higher than 30 kPa and gives  $c = 0$  and  $\phi = 33^\circ$ :

$$\text{For } \sigma < 30 \text{ kPa, } \quad s = 24 \text{ kPa} \quad (24.32)$$

$$\text{For } \sigma > 30 \text{ kPa, } \quad s = \sigma \tan 33 = 0.65 \sigma \quad (24.33)$$

Kavazanjian (1999) suggested a shear wave velocity for MSW which varies from 150 m/s at the surface to 350 m/s at a depth of 60 m. For compressibility, most investigators favor the consolidation equation (see section 17.8.9):

$$\Delta H = H_o \frac{C_c}{1 + e_o} \log \left( \frac{\sigma'_{ov} + \Delta\sigma_v}{\sigma'_{ov}} \right) \quad (24.34)$$

where  $\Delta H$  is the settlement,  $H_o$  is the initial thickness of the waste layer,  $C_c$  is the compression index,  $e_o$  is the initial void ratio,  $\sigma'_{ov}$  is the effective vertical stress before loading, and  $\sigma'_{ov} + \Delta\sigma_v$  is the effective stress long after loading. Values of  $C_c/(1 + e_o)$  between 0.1 to 0.4 have been suggested (Navfac 1983), with the higher values corresponding to higher organic content. With MSW, a significant amount of delayed settlement (*creep*) can be expected over 10 to 15 years, with the magnitude of  $\Delta H/H_o$  as much as 50% for new landfills

and 15 to 20% for old landfills (Sharma and Reddy 2004). The creep settlement equation is written as:

$$\Delta H = H_o \frac{C_\alpha}{1 + e_o} \log \left( \frac{t_{end}}{t_{start}} \right) \quad (24.35)$$

where  $\Delta H$  is the creep settlement,  $H_o$  is the layer thickness,  $e_o$  is the initial void ratio,  $C_\alpha$  is the secondary compression index,  $t_{start}$  is the start time, and  $t_{end}$  is the end time. Values of  $C_\alpha/(1 + e_o)$  have been reported (Sharma 2000) as varying from 0.1 to 0.4, with the higher values for higher organic content and higher degree of decomposition of the waste.

### 24.7.2 Regulations

The U.S. Resource Conservation and Recovery Act (RCRA) was passed in 1970 and amended in 1980 and 1984. Subtitle D of RCRA applies to MSW landfills, whereas subtitle C of RCRA applies to hazardous solid waste landfills. The issues covered are location, operation, design, monitoring, closure, and postclosure. Restrictions exist when landfill locations are proposed near airports, wetlands, floodplains, and fault areas. The surface area  $A$  required for a landfill in a city is calculated by:

$$A = \frac{WPt}{D\gamma} \quad (24.36)$$

where  $W$  is the weight of waste generated by a person per day,  $P$  is the total population of the city,  $t$  is the design period for the landfill,  $D$  is the depth of the landfill, and  $\gamma$  is the unit weight of the compacted landfill. The weight generated by one person per day is about 20 N. The unit weight of waste in a landfill varies widely, with an average of around 8 kN/m<sup>3</sup>. The period  $t$  varies from 10 to 30 years, and the depth  $D$  is between 10 and 30 m.

There are many aspects to operating a landfill properly. First, a daily cover of about 0.3 m thick coarse-grained soil is required to cover the waste that was brought in that day. Other aspects include monitoring of the gas generated by the waste, control of public access, control of discharge and surface water, and recordkeeping regarding compliance.

One of the main components of the design of a landfill is the bottom composite liner, with a leachate collection system, a gas venting system, and a groundwater monitoring system; the top cover is another primary component. Closure takes place when the final cover is completed. Mandatory postclosure activities including maintenance of the top cover and of the leachate collection system, as well as monitoring of the gas generated and the groundwater, must continue for 30 years.

### 24.7.3 Liners

*Liners* are barriers constructed at the bottom and on the side of landfills. Their purpose is to keep the waste and any by-product(s) out of the surrounding soil and groundwater. For municipal solid waste landfills, the liner composition is specified by RCRA Subtitle D (40 C.F.R. 258), and consists of a series of layers performing different functions. Going from the top to the bottom of the bottom liner, the following layers (2 through 6 for the liner) are encountered (Figure 24.21):

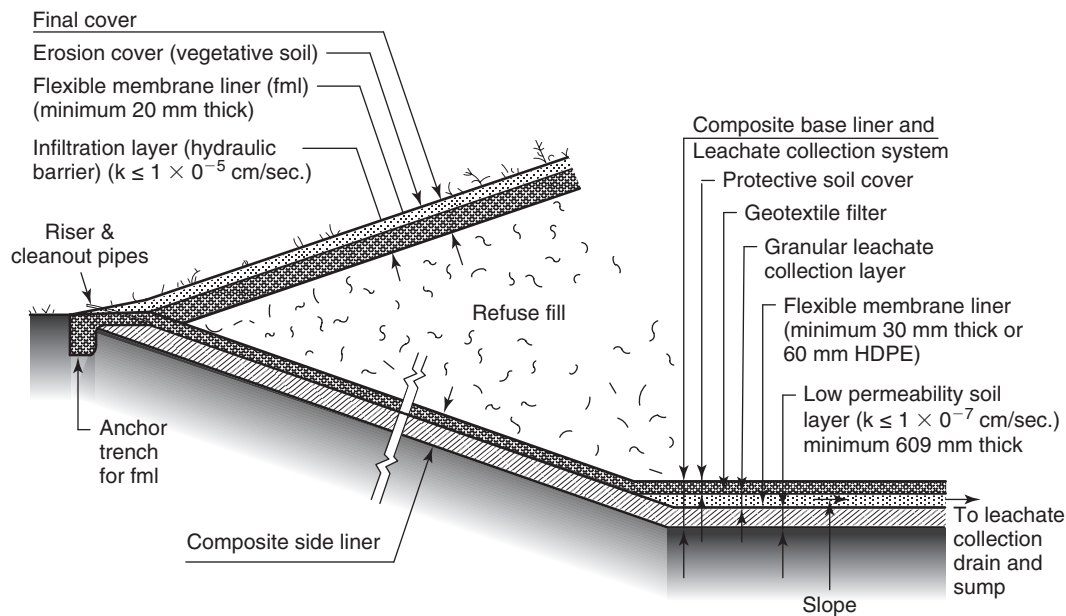
1. Waste
2. Protective soil cover to minimize damage to the underlying geotextile
3. Geotextile layer that acts as a filter for any liquid coming down from the waste
4. Coarse-grained soil layer to serve as a leachate collection system

5. Geomembrane layer to prevent liquid penetration into the underlying layers; this geomembrane must be at least 0.75 mm thick for a flexible membrane liner and 1.5 mm thick for a high-density polyethylene (Figure 24.22)
6. Low-permeability soil layer ( $k < 10^{-9}$  m/s) with a minimum thickness of 0.6 m
7. Natural soil

The liner should have a slope so that the leachate can drain naturally by gravity, be collected at a low point or sump, and be pumped and treated on a regular basis. The liner on



**Figure 24.22** Installing a geomembrane in a bottom liner. (Courtesy of Layfield Environmental Systems, Layfield Group Limited, 11120 Silversmith Place, Richmond, British Columbia, Canada V7A 5E4.)



**Figure 24.21** Landfill cover and bottom liner composition for municipal solid wastes. (After Sharma and Reddy, 2004. This material is reproduced with permission of John Wiley & Sons, Inc.).

the side slopes is the same as the bottom liner except that it does not typically have a leachate collection layer. The leachate naturally goes to the bottom of the landfill, where it is collected in the leachate collection layer.

For hazardous solid waste landfills, the liner composition is specified by RCRA Subtitle C (40 C.F.R. 244) with a series of layers as follows. Going from the top to the bottom of the bottom liner, the following layers (2 through 6 for the liner) are encountered:

1. Waste.
2. Protective soil cover (optional) to minimize damage to the underlying geomembrane.
3. Geomembrane to act as a barrier for any liquid coming down from the waste. This geomembrane must be at least 0.76 mm thick if there is a protective soil layer above it or at least 1.14 mm thick if there is no protective layer above. For HDPE liners, the minimum required thickness is larger, varying from 1.5 to 2.5 mm.
4. Coarse-grained soil layer to serve as a leachate collection system.
5. Geomembrane layer to serve as a barrier preventing liquid penetration into the underlying layers.
6. Low-permeability soil layer ( $k < 10^{-9}$  m/s) with a minimum thickness of 0.9 m.
7. Natural soil.

As can be seen, a municipal solid waste liner is a single liner, whereas a hazardous solid waste liner is a double liner with the leachate collection system sandwiched between the two liners.

The geomembranes and geotextiles used in landfill liners are discussed in Chapter 25. The hydraulic conductivity  $k$  of the liner must be less than  $10^{-9}$  m/s. The hydraulic conductivity  $k$  of soils is discussed in sections 13.2.5 and 13.2.6. The measurement of  $k$  in the laboratory is discussed in sections 9.16 to 9.19 and in the field in section 7.12. The  $k$  values of clays permeated by contaminated liquids may differ significantly from the values obtained with water because of the chemistry of the permeating fluid. Various experiments starting in the late 1980s (e.g., Bowders and Daniel 1987; Shackelford 1994) indicated that when a clay is permeated with different chemicals, the hydraulic conductivity changes—sometimes dramatically. For example, a high concentration of methanol or heptane or trichloroethylene in the fluid will increase  $k$ ; this is because such chemicals decrease the thickness of the clay particle double layer. In contrast, diluted acid in the permeating fluid will tend to decrease the value of  $k$  because the acid can create precipitates that clog the clay pores and render flow more difficult; however,  $k$  will likely increase in the long term. One first step in gauging whether a chemical will alter the hydraulic conductivity of a soil is to investigate the change in Atterberg limits when the soil is mixed with the chemical; note, though, that the link between the effect on Atterberg limits and  $k$  is not always clear. Mitchell and Madsen (1987) concluded that permeation with hydrocarbons

may affect  $k$ , but only if the concentration in the permeating fluid exceeds their solubility limit. Similar caution should be exercised for geosynthetic bentonite-clay liners (Shackelford 2000). In all cases, it is best to run site-specific tests with the clay from the site and the anticipated fluid, including the appropriate chemical concentration.

#### 24.7.4 Covers

Covers (Figure 24.21) are placed on top of landfills that are full and must be closed. A cover has many purposes, including minimizing the infiltration of rainwater, decreasing the hydraulic head on the bottom liner, resisting surface erosion, keeping away rodents and insects, controlling gas emissions, and improving aesthetics. The typical cross section of a cover consists of a series of layers (1 through 5) as follows:

1. Vegetative layer for aesthetics and erosion protection.
2. Protective soil layer (optional).
3. Drainage layer to collect water, made of gravel and sand.
4. Barrier layer to stop water from penetrating into the waste. This layer may consist of a compacted clay layer, a geosynthetic clay liner (GCL), a geomembrane, or combinations thereof.
5. Drainage layer to collect gas generated by the waste, made of sand and gravel or geotextile.
6. Waste.

The specifications for covers of hazardous solid waste landfills (RCRA subtitle C) are more stringent than for covers of municipal solid waste landfills (RCRA subtitle D). For hazardous wastes, the required thickness of the layers is larger than for municipal wastes.

The final elevation of the top of a landfill is usually higher than the surrounding ground elevation (Figure 24.23). The side slopes of the final cover may be at  $24^\circ$  with the horizontal if the cover is made of soil layers, but it may be prudent to have the slopes at only  $18^\circ$  if a geomembrane is included in the cover, unless special measures to improve geomembrane roughness are taken. The top of the landfill is also sloped, but only at 2 to 5% on either side of the center to provide natural drainage.

#### 24.7.5 Leachate Collection

The amount of leachate that would go through a single compacted clay liner is given by:

$$q = k \frac{\Delta h}{L} A \quad (24.37)$$

where  $q$  is the flow in  $\text{m}^3/\text{s}$ ,  $k$  is the soil hydraulic conductivity in  $\text{m/s}$ ,  $\Delta h$  is the change in total head when crossing the compacted clay layer,  $L$  is the length of the flow path through the liner (thickness), and  $A$  is the plan view area of the liner. The hydraulic conductivity  $k$  is required by design to be less than  $10^{-9}$  m/s, so this is the number used in Eq. 24.37. The

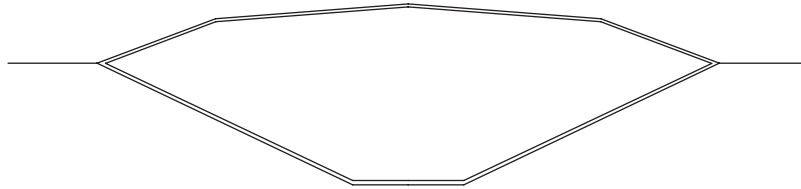


Figure 24.23 General cross section of a landfill.

change in total head  $\Delta h$  is usually taken as the sum of the height of liquid standing on top of the liner plus the thickness of the liner. This assumes that the total head under the liner is zero.

A *composite liner* is made of a geomembrane underlain by a compacted clay liner. The amount of leachate that would go through a composite liner was studied by Giroud and Bonaparte (1989), who recommended the following equation:

$$q = \frac{a^{0.1} k^{0.88} h_w A}{170000} \quad (24.38)$$

where  $q$  is the flow in  $\text{m}^3/\text{s}$ ,  $a$  is the cumulative area of holes in the geomembrane in  $\text{m}^2$  per acre ( $4047 \text{ m}^2$ ),  $k$  is the soil hydraulic conductivity in  $\text{m/s}$ ,  $h_w$  is the height of liquid on top of the geomembrane in  $\text{m}$ , and  $A$  is the area of the bottom liner over which the flow of leachate  $q$  is calculated. Furthermore, Giroud and Bonaparte (1989) recommend assuming one hole of  $3.2 \text{ mm}^2$  per  $4047 \text{ m}^2$  of geomembrane under operating conditions, but a much larger hole for conservative sizing of the leachate collection system. For sizing purposes, they recommend a hole of  $103 \text{ mm}^2$  per  $4047 \text{ m}^2$  of geomembrane.

A cover is exposed to rain, runoff, and evaporation. The amount of leachate through a cover's top layer is calculated as follows:

$$I = P - R - E \pm \Delta S \quad (24.39)$$

where  $I$  is the infiltration,  $P$  is the precipitation,  $R$  is the runoff,  $E$  is the evapotranspiration, and  $\Delta S$  is the change in water volume per unit time of the soil cover. All terms in Eq. 24.39 take the same units ( $\text{m}^3/\text{yr}$ , for example). If there is no cover on the waste, as is the case during operation, the amount of leachate reaching the bottom liner should be reflected by adding another term to Eq. 24.39, to represent the amount of liquid generated by the waste itself by compression or by chemical reaction.

The leachate collection system within covers and liners is built with a slope such that the leachate flows downward in the drainage layer toward a sump. At the sump, the leachate is collected and pumped to the surface, where it is analyzed and treated.

### 24.7.6 Landfill Slopes

The topic of slope stability is covered in Chapter 19. In the case of a landfill, slope stability comes into play in a number of instances (Figure 24.24), including the side slopes of the excavation, the stability of the side slope liner at the time of construction, the stability of the side slope liner when loaded unevenly by the waste pile, the stability of the waste when the landfilling operation advances through the landfill area, and the stability of the waste and cover upon closure of the landfill.

The stability of the side slope of the excavation can be addressed by using the methods described in Chapter 19. The stability of the waste, for the case of a failure in the waste itself, can also be addressed using conventional methods, except that the shear strength of the waste may or may not follow soil mechanics principles (section 24.7.1). The stability of the side slope liner is the case of a thin and long slope feature; it can be addressed by using the infinite slope method (see section 19.3). The stability of the side slope liner when loaded by the waste is usually a controlling factor in design because it is more severe than the case of the liner by itself. In this case, the most likely failure mechanism is a block failure along the side and bottom liner, because the liner may be the weak link in the resistance to shear. Thus, it is best not to have the front face of the waste at a steep slope. One important issue is the shear strength of the interface between the various materials making up the liner. Each interface should be checked and the associated factor of safety calculated. Factors of safety between 1.3 and 1.5 are common.

The interfaces involve the geomembrane, the geotextile, the geosynthetic clay liner (GCL), the drainage layer, the natural soil, and the waste. The geomembrane should be textured rather than smooth, to improve its interface shear strength,

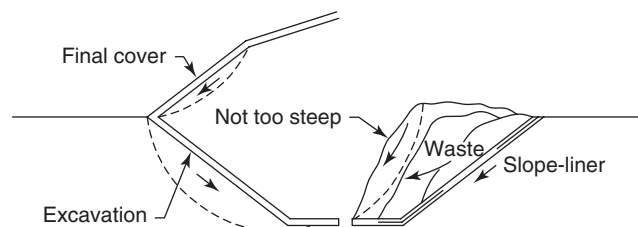
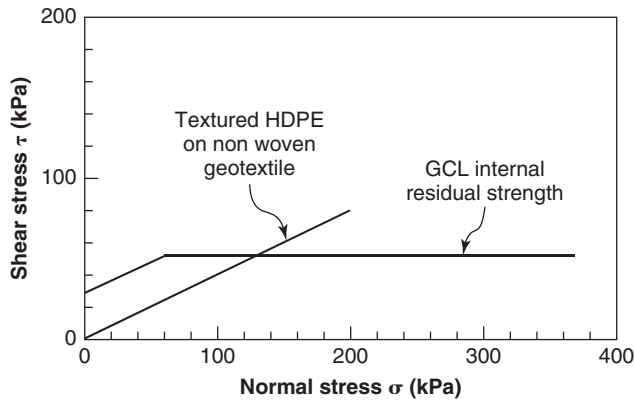


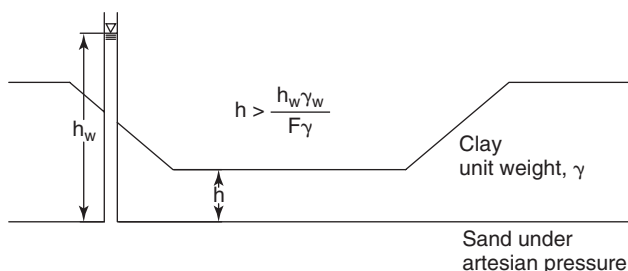
Figure 24.24 Slope stability design issues in a landfill



**Figure 24.25** Strength envelopes of various interfaces (After Sharma et al. 1997)

and the GCL should be stitched to dramatically increase the shear strength of the bentonite layer. The best way to obtain design values for the interface shear strength is to perform direct shear strength tests (ASTM D5321 and D 6143) on site-specific materials under simulated field conditions. Some aspects of the behavior are important to document: the peak shear strength, the postpeak residual shear strength, the influence of the normal stress level, and the nonlinearity of the strength envelope. It is useful to place all shear strength envelopes on the same graph when the tests are completed (Figure 24.25) to find out which of the interfaces is the weak link for a given normal stress. A seismic slope analysis is also necessary (see section 19.18).

An additional problem may arise when during construction of the landfill, the excavation proceeds through a clay layer with an underlying sand layer under artesian pressure (Figure 24.26). Though this case is rare, it can be disastrous, because if the excavation is dug to a depth where the water pressure ( $\gamma_w h_w$ ) at the top of the sand layer overcomes the downward pressure of the clay remaining on top of the sand ( $\gamma h$ ), the bottom of the excavation will blow up and a mixture of sand and water will run into the excavation. A factor of safety must be applied to the maximum depth of excavation to guard against such an event. The safe remaining thickness



**Figure 24.26** Blowout problem at bottom of excavation.

h of the clay layer is:

$$h = \frac{\gamma_w h_w}{F \gamma} \quad (24.40)$$

### 24.7.7 Gas Generation and Management

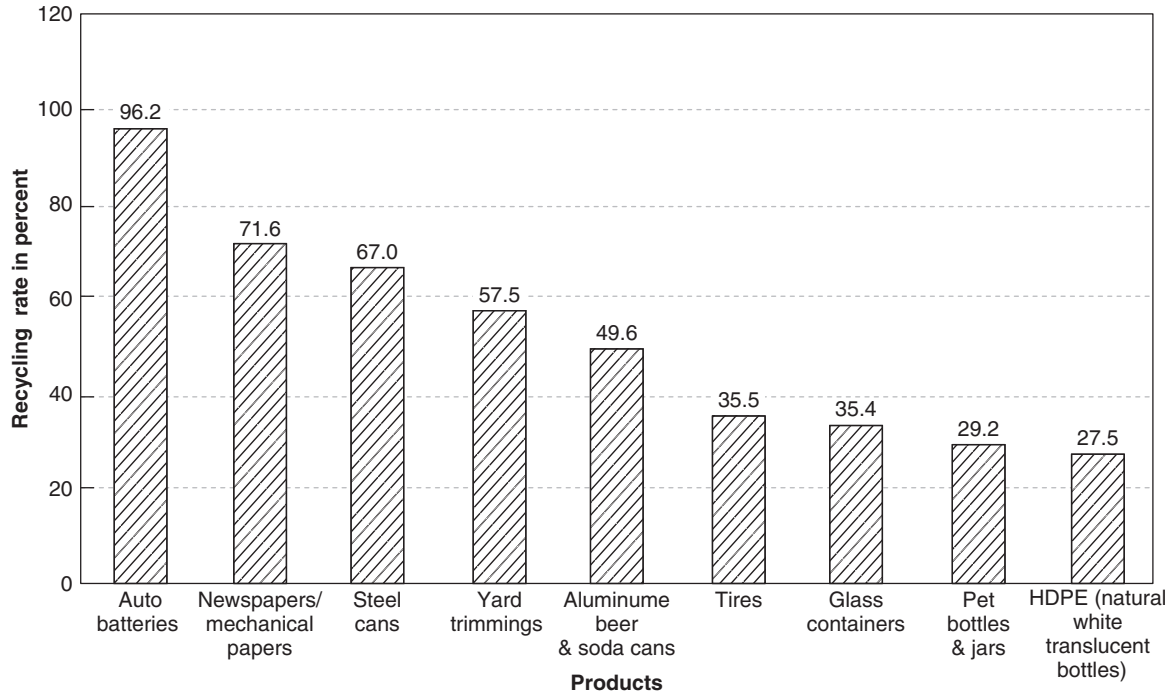
Landfills generate gas, mostly carbon dioxide and methane, through biodegradation. These gases are flammable, are toxic to humans, can create excessive deformation of the liners, and smell bad. Furthermore, methane is a greenhouse gas. The gas generation process is due to the work of bacteria that transform some of the waste through digestion. The product is approximately 50% carbon dioxide (CO<sub>2</sub>) and 50% methane (CH<sub>4</sub>). The carbon dioxide is usually generated first, followed by the methane. The intensity of this process depends on a number of factors, including the availability of nutrients for the bacteria, temperature, humidity, pH, and age of the waste. Landfill temperatures vary from 20 to 60°C. Higher temperature and higher water content of the waste are more favorable to gas generation, which can reach 10,000 m<sup>3</sup> per kN of waste over the life of the landfill. Gas generation in a landfill does have a finite life, which can vary from 20 years under favorable conditions where biodegradation is rapid (e.g., humid climates) to 100 years under unfavorable conditions where biodegradation is slow (e.g., arid climates).

The gas generated must be disposed of and the disposal process monitored. There are essentially three ways to dispose of gasses: vent to the atmosphere, vent and burn with no energy recovery, and vent and burn with energy recovery. The most common of the three is vent and burn without energy recovery, through the use of flares. Venting is achieved by placing gas wells into the waste, which facilitate gas migration to the surface where the gas is burned. Old landfills used open flame flares, which are the simplest kind, but modern landfills use enclosed flares because they allow for measurement of the gas coming out of the waste and yield better overall control. Wells typically consist of perforated pipes 50 to 300 mm in diameter that extend to 75% of the full depth of the landfill. The spacing varies from 15 to 100 m and averages 60 m. The energy recovery systems use the gas to power gas turbines or combustion engines to generate electricity, but the initial cost of such a system is worth the investment only for large landfills with more than 10 million kN of waste.

## 24.8 FUTURE CONSIDERATIONS

Lowering the generation of waste at the source is the first and best way to decrease the amount of waste generated by humankind. Recycling is the second best option. Recycling of household waste or municipal solid waste has become part of everyday life, and over the past 20 years has reduced the amount of waste going to landfills to about 50% of the MSW generated (Figure 24.27). The most successful programs have been recycling of aluminum and paper, because in both cases the cost-benefit ratio is favorable. Recycling does not stop at





**Figure 24.27** Recycling rate for various waste products in 2011 (Source: EPA).



**Figure 24.28** Postclosure use of landfills.

household waste, but extends as well to the industrial sector, which is by far the largest generator of waste. Efforts for recycling fly ash, blast furnace slag, foundry sand, paper mill sludge, incinerator ash, glass, plastics, scrap tires, demolition

and concrete debris, and wood waste are being made (Sharma and Reddy 2004). Note that once landfills are closed, the area can be used for various activities including parks, golf courses, airports, and sports stadiums (Figure 24.28).

## PROBLEMS

- 24.1 How do you define waste?
- 24.2 What is the biggest generator of waste in the United States?
- 24.3 Are solid wastes solids?
- 24.4 What are the four main categories of waste?
- 24.5 How long can a high-level radioactive waste continue to be deadly?
- 24.6 What are RCRA and CERCLA and what do they regulate?
- 24.7 What does an OSHA level C mean and what does it require?
- 24.8 What is the name of the smallest piece of matter and what are its components?
- 24.9 What is the difference between an atom and a molecule?
- 24.10 What is the difference between an ion, an anion, and a cation?
- 24.11 In the case of concentration in water, how many parts per million (ppm) are in  $1 \text{ mg/m}^3$ ?

- 24.12 What is the difference between organic and inorganic materials?
- 24.13 What is the difference between atomic absorption spectrophotometry (AAS) and gas chromatography-mass spectrometry (GC-MS)?
- 24.14 What are ESA I, II, and III, and when are they used?
- 24.15 What is the difference between the LIF CPT, the MIP CPT, and the BAT CPT?
- 24.16 In contaminant transport, what is the difference between concentration and flux?
- 24.17 Choose some reasonable values of the parameters in the solution to contamination propagation (Eq. 24.29) and draw the propagation plot. Then vary each parameter to understand the influence each one has on the propagation. For help with the solution, go to [www.lmnoeng.com/Groundwater/transportStep.htm](http://www.lmnoeng.com/Groundwater/transportStep.htm)
- 24.18 How can you form a bottom barrier at depth for a waste containment system?
- 24.19 A landfill has been closed for one day and the long-term settlement must be evaluated. The waste is 15 m deep, has a unit weight of  $8 \text{ kN/m}^3$ , and has a  $C_a/(1 + e_o)$  coefficient equal to 0.2. Calculate the creep settlement after 20 years.
- 24.20 Calculate the area of the landfill necessary to handle the municipal solid waste generated by a city of 1 million people over a period of 10 years. Each person in that city generates 20 N of MSW per day. The depth to the water table is 20 m and a high-plasticity clay layer exists at a depth of 15 m.
- 24.21 Calculate the flow of leachate through a 0.6 m thick clay liner covering a  $200 \text{ m} \times 200 \text{ m}$  area. The leachate level is 0.4 m above the top of the liner and the hydraulic conductivity of the clay meets the specification of  $10^{-9} \text{ m/s}$ .
- 24.22 Chloride dissolved in water is leaching through a liner and permeating into an aquifer-bearing 2 m thick layer of silty sand. The concentration of the dissolved chloride is 1500 mg/liter, the discharge velocity is  $3.7 \times 10^{-7} \text{ m/s}$ , and the porosity of the silty sand is 0.25. Calculate the mass flux of chloride into the aquifer per unit area of landfill liner due to advection.
- 24.23 Calculate the flow of leachate through a composite liner with a 0.75 m thick compacted clay layer over an HDPE geomembrane. The clay has a hydraulic conductivity of  $10^{-9} \text{ m/s}$  and the HDPE membrane is 1.5 mm thick. The height of liquid above the geomembrane is 0.2 m. Give the answer for expected operating conditions first and then give a more conservative estimate for sizing the leachate pumping system.
- 24.24 An excavation is dug for a landfill in a 20 m thick stiff, high-plasticity clay layer underlain by a sand layer under artesian pressure. The unit weight of the clay is  $19 \text{ kN/m}^3$  and that of the sand is  $20 \text{ kN/m}^3$ . The artesian pressure is such that a casing through the clay into the sand has water rising 10 m above the top of the clay layer (ground surface). How deep can the excavation be dug into the clay to maintain a minimum factor of safety of 1.5 against bottom blowout failure? Draw the effective vertical stress profile before and after excavation to that depth.

## Problems and Solutions

### Problem 24.1

How do you define waste?

### Solution 24.1

*Waste* is unwanted or useless material.

### Problem 24.2

What is the biggest generator of waste in the United States?

### Solution 24.2

The industrial sector is the largest generator of waste.

### Problem 24.3

Are solid wastes solids?

### Solution 24.3

No. The term *solid waste* is misleading, as a solid waste can be a solid, a liquid, or a gas.

**Problem 24.4**

What are the four main categories of waste?

**Solution 24.4**

The four main categories of waste are: solid wastes, hazardous wastes, radioactive wastes, and medical wastes.

**Problem 24.5**

How long can a high-level radioactive waste continue to be deadly?

**Solution 24.5**

The radiation penetration from high-level wastes, which are generated by defense or nuclear power plant activities, remains lethal for 10,000 years.

**Problem 24.6**

What are RCRA and CERCLA and what do they regulate?

**Solution 24.6**

RCRA is the Resource Conservation and Recovery Act; it addresses the issue of landfill design. CERCLA is the Comprehensive Environmental Response, Compensation, and Liabilities Act; it addresses the issue of cleaning up contaminated sites.

**Problem 24.7**

What does an OSHA level C mean and what does it require?

**Solution 24.7**

OSHA stands for Occupational Safety and Health Administration. OSHA level C refers to moderate protection for humans working at contaminated sites. That is, it requires moderate protection including full-face or half-mask air-purifying respirator, hooded chemical-resistant clothing, inner and outer chemical-resistant gloves, chemical-resistant boots and boot covers, hard hat, escape mask, and face shield.

**Problem 24.8**

What is the name of the smallest piece of matter and what are its components?

**Solution 24.8**

An atom is the smallest piece of matter. Atoms are made of protons, electrons, and neutrons

**Problem 24.9**

What is the difference between an atom and a molecule?

**Solution 24.9**

Atoms consist of a nucleus containing protons and neutrons with electrons surrounding the nucleus; they are the basic building blocks of matter (e.g., hydrogen atom). Molecules are combinations of atoms bonded together. For example, two hydrogen atoms and an oxygen atom form a molecule of water ( $\text{H}_2\text{O}$ ).

**Problem 24.10**

What is the difference between an ion, an anion, and a cation?

**Solution 24.10**

*Ion* is the general term for an atom that has lost or gained an electron on its outer orbital. More specifically, an ion can be a cation or an anion. *Cations* are neutral atoms that have lost one or more electrons, making them positively charged, such as  $\text{Na}^+$ ,  $\text{Ca}^{++}$ , and  $\text{Al}^{+++}$ . *Anions* are the opposite: They have gained one or more electrons and thus have a net negative charge, such as  $\text{Cl}^-$ ,  $\text{O}^-$ , and  $\text{N}^-$ .

**Problem 24.11**

In the case of concentration in water, how many parts per million (ppm) are in  $1 \text{ mg/m}^3$ ?

**Solution 24.11**

For the mass concentration of a chemical in water,  $1 \text{ ppm} = 1 \text{ mg/liter}$  and  $1 \text{ liter} = 0.001 \text{ m}^3$ . Therefore, there are 0.001 ppm in  $1 \text{ mg/m}^3$ .

**Problem 24.12**

What is the difference between organic and inorganic materials?

**Solution 24.12**

The difference between organic and inorganic compounds is that most organic compounds contain carbon, whereas most inorganic compounds do not.

**Problem 24.13**

What is the difference between atomic absorption spectrophotometry (AAS) and gas chromatography-mass spectrometry (GC-MS)?

**Solution 24.13**

GC-MS is used to identify the components of a chemical mixture. AAS is used to measure the molar concentration of chemicals.

**Problem 24.14**

What are ESA I, II, and III, and when are they used?

**Solution 24.14**

Environmental site assessments or ESAs are part of the contamination detection process. They are often required when purchasing a piece of property in the United States. There are three levels:

*ESA I:* This phase consists of collecting information regarding previous ownership and prior use through records of contaminated sites in the area, aerial photos, geologic and topographic maps, visits to the site, and talking to neighbors. An ESA I indicates whether there are reasons to believe the site is contaminated. If so, ESA II comes into play.

*ESA II:* This phase consists of testing the soil and the groundwater to find out if there is contamination and, if there is, to what extent and to what level of severity (type of contaminants). If contamination that requires cleanup is found, ESA III comes into play.

*ESA III:* This phase consists of designing the remediation scheme and achieving it, including verification that a satisfactory level of cleanup has been realized.

**Problem 24.15**

What is the difference between the LIF CPT, the MIP CPT, and the BAT CPT?

**Solution 24.15**

LIF (laser-induced fluorescence) is a CPT technique used to determine the extent of plumes at petroleum-contaminated sites and the type of petroleum product contaminating the site. A laser beam is shone on the soil, which emits different fluorescence depending on the hydrocarbon present.

MIP (membrane interface probe) is a CPT technique used to identify the type of volatile organic compound by heating the soil and letting the gas permeate through a membrane located on the side of the CPT. Once in the CPT housing, the gas is swept by an inert carrier gas to the surface where it is analyzed.

BAT is a CPT technique used to collect groundwater. (BAT is the name of a company.) The CPT probe is equipped with a porous filter that is obstructed until the CPT probe is pushed to the required depth. Then the filter is exposed and water is allowed to penetrate through the filter into a water sampling tube, which can be removed through the CPT rods when full.

**Problem 24.16**

In contaminant transport, what is the difference between concentration and flux?

**Solution 24.16**

Concentration  $C$  is the mass of contaminant (solute) per volume of liquid carrying the contaminant (solvent); it is measured in  $\text{kg}/\text{m}^3$ .

Flux  $F$  is the mass of contaminant flowing through a unit area of soil per unit of time; it is measured in  $\text{kg}/\text{m}^2\text{s}$ .

They are related through  $F = Cv$ .

**Problem 24.17**

Choose some reasonable values of the parameters in the solution to contamination propagation (Eq. 24.29) and draw the propagation plot. Then vary each parameter to understand the influence each one has on the propagation. For help with the solution, go to [www.lmnoeng.com/Groundwater/transportStep.htm](http://www.lmnoeng.com/Groundwater/transportStep.htm)

**Solution 24.17**

$$C_w(x, t) = \frac{C_0}{2} \operatorname{erfc} \left( \frac{R_d x - v_s t}{\sqrt{4 R_d D_H t}} \right)$$

$C_0$  = Constant contaminant concentration at point  $X = 0$  and  $t = 0$

$X$  = Distance

$V_s$  = Seepage velocity

$R_d$  = Retardation factor  $R_d = 1 + \frac{\rho_d K_d}{n}$  where  $\rho_d$  is dry density and  $n$  is total porosity

$K_d$  = Partition coefficient

$D_H$  = Hydrodynamic dispersion  $D_H = D^* + \alpha_L v_s$  where  $\alpha_L$  dispersivity varies from 0.1 to 100

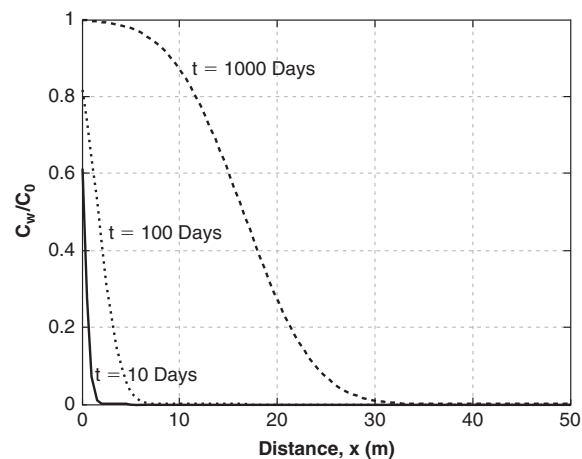
$D^*$  = Molecular diffusion coefficient; typical value  $1 \times 10^{-9}$  ( $\text{m}^2/\text{s}$ )

Propagation of the contamination is plotted as normalized concentration  $C_w/C_0$  versus  $x$  for the following input parameters:

$$\alpha_L = 100, \rho_d = 1.6(\text{g}/\text{cm}^3), n = 35 (\%), D^* = 1 \times 10^{-5} (\text{cm}^2/\text{s}),$$

$$v_s = 1.92e - 5 (\text{cm}/\text{s}), K_d = 0.1 (\text{cm}^3 \text{ g}), t = 1000 (\text{days})$$

- Propagation plot (Figure 24.1s)



**Figure 24.1s** Propagation plot.

- Varying parameter  $\alpha_L$  (Figure 24.2s)

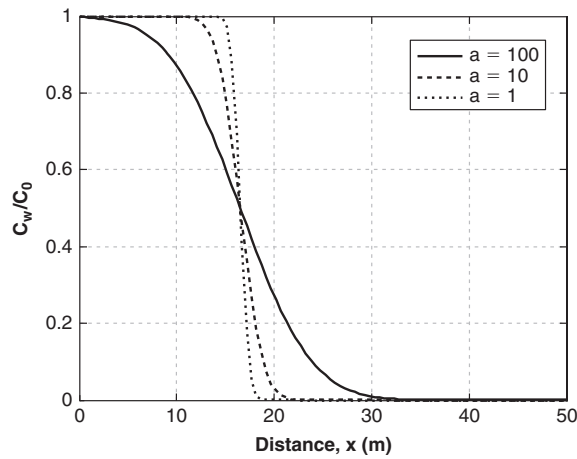


Figure 24.2s Propagation plot for different values of  $\alpha_L$ .

- Varying parameter  $\nu_s$  (Figure 24.3s)

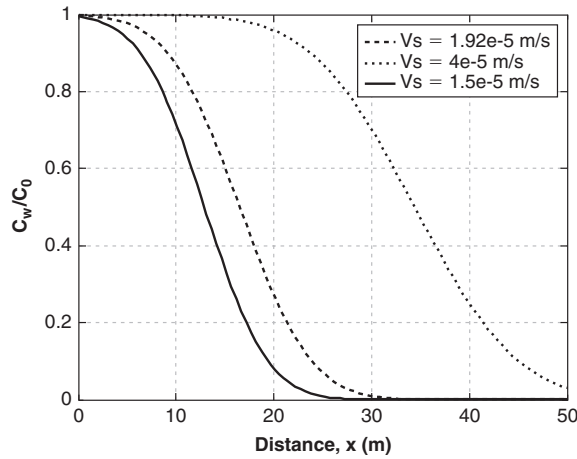


Figure 24.3s Propagation plot for different values of  $\nu_s$ .

- Varying parameter  $\rho_d$  (Figure 24.4s)

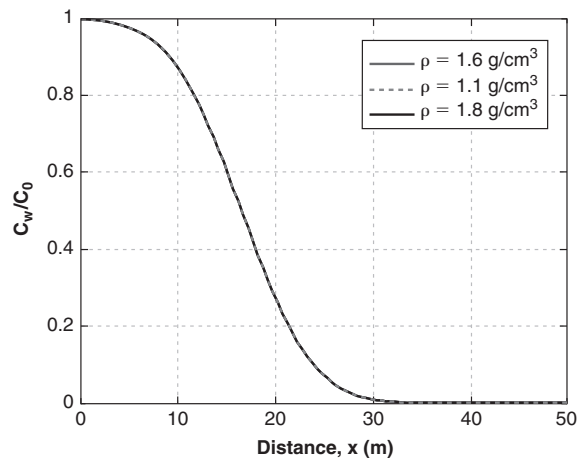


Figure 24.4s Propagation plot for different values of  $\rho_d$ .

**Problem 24.18**

How can you form a bottom barrier at depth for a waste containment system?

**Solution 24.18**

A bottom barrier can be constructed by grouting or directional drilling.

Grouting can be pressure grouting or jet grouting, but in both cases the injection pipe is driven or vibrodriven to the depth of the bottom barrier and a grout bulb is constructed. The operation is repeated until the overlapping bulbs form a bottom barrier. The drawback with this technique is that holes have to be punched through the waste or contaminated zone.

Directional drilling consists of setting an inclined drill outside of the contaminated zone and drilling at an angle to reach underneath that zone. Then the hole is grouted. Side-by-side holes are drilled and grouted to form the bottom barrier.

**Problem 24.19**

A landfill has been closed for one day and the long-term settlement must be evaluated. The waste is 15 m deep, has a unit weight of  $8 \text{ kN/m}^3$ , and has a  $C_\alpha/(1 + e_0)$  coefficient equal to 0.2. Calculate the creep settlement after 20 years.

**Solution 24.19**

$$\Delta H = H_0 \frac{C_\alpha}{1 + e_0} \log \left( \frac{t_{\text{end}}}{t_{\text{start}}} \right) = 15 \text{ m} * 0.06 * \log \left( \frac{20 * 365 \text{ day}}{1 \text{ day}} \right) = 3.48 \text{ m}$$

**Problem 24.20**

Calculate the area of the landfill necessary to handle the municipal solid waste generated by a city of 1 million people over a period of 10 years. Each person in that city generates 20 N of MSW per day. The depth to the water table is 20 m and a high-plasticity clay layer exists at a depth of 15 m.

**Solution 24.20**

The surface area  $A$  required for a landfill in a city is calculated by:

$$A = WPtD\gamma$$

where  $W$  is the weight of waste generated by a person per day,  $P$  is the total population of the city,  $t$  is the design period for the landfill,  $D$  is the depth of the landfill, and  $\gamma$  is the unit weight of the compacted landfill (estimated at  $8 \text{ kN/m}^3$ ).

The depth of the water table is 20 m, and there is high-plasticity clay at depth 15 m, so the depth of landfill is selected as 15 m:

$$A = \frac{20 \text{ N/day} \times 10^6 \times 3650 \text{ day}}{15 \text{ m} \times 8 \text{ kN/m}^3} = \frac{7.3 \times 10^7 \text{ kN}}{1.2 \times 10^2 \text{ kN/m}^2} = 6.08 \times 10^5 \text{ m}^2$$

**Problem 24.21**

Calculate the flow of leachate through a 0.6 m thick clay liner covering a  $200 \text{ m} \times 200 \text{ m}$  area. The leachate level is 0.4 m above the top of the liner and the hydraulic conductivity of the clay meets the specification of  $10^{-9} \text{ m/s}$ .

**Solution 24.21**

The amount of leachate that would go through a single compacted clay liner is calculated by  $q = K \frac{\Delta h}{L} A$ , where  $q$  is the flow in  $\text{m}^3/\text{s}$ ,  $k$  is the soil hydraulic conductivity in  $\text{m/s}$ ,  $\Delta h$  is the change in total head when crossing the compacted clay layer,  $L$  is the length of the flow path through the liner (thickness), and  $A$  is the plan view area of the liner:

$$\Delta h = 0.6 + 0.4 = 1 \text{ m}$$

$$A = 200 \times 200 = 40000 \text{ m}^2$$

$$q = K \frac{\Delta h}{L} A = 10^{-9} \times \frac{1}{0.6} \times 40000 = 6.67 \times 10^{-5} \text{ m}^3/\text{s}$$

**Problem 24.22**

Chloride dissolved in water is leaching through a liner and permeating into an aquifer-bearing 2 m thick layer of silty sand. The concentration of the dissolved chloride is 1500 mg/liter, the discharge velocity is  $3.7 \times 10^{-7} \text{ m/s}$ , and the porosity of the silty sand is 0.25. Calculate the mass flux of chloride into the aquifer per unit area of landfill liner due to advection.

**Solution 24.22**

$$F_{adv} = vC = nv_s C = 3.7 \times 10^{-7} \times 1500 \times 10^{-3} = 5.55 \times 10^{-7} \text{ mg/m}^2 \text{ s}$$

**Problem 24.23**

Calculate the flow of leachate through a composite liner with a 0.75 m thick compacted clay layer over an HDPE geomembrane. The clay has a hydraulic conductivity of  $10^{-9}$  m/s and the HDPE membrane is 1.5 mm thick. The height of liquid above the geomembrane is 0.2 m. Give the answer for expected operating conditions first and then give a more conservative estimate for sizing the leachate pumping system.

**Solution 24.23**

$$q = \frac{a^{0.1} k^{0.88} h_w A}{170000}$$

**Case 1: Operating conditions**

$$q = \frac{\left(\frac{3.2 \times 10^{-6}}{4047}\right)^{0.1} \times (10^{-9})^{0.88} \times 0.2 \times 1}{170000} = 1.73 \times 10^{-15} \text{ m}^3/\text{s} = 0.55 \text{ cm}^3/\text{year}$$

**Case 2: Pumping system design**

$$q = \frac{\left(\frac{103 \times 10^{-6}}{4047}\right)^{0.1} \times (10^{-9})^{0.88} \times 0.2 \times 1}{170000} = 2.64 \times 10^{-15} \text{ m}^3/\text{s} = 0.83 \text{ cm}^3/\text{year}$$

**Problem 24.24**

An excavation is dug for a landfill in a 20 m thick stiff, high-plasticity clay layer underlain by a sand layer under artesian pressure. The unit weight of the clay is  $19 \text{ kN/m}^3$  and that of the sand is  $20 \text{ kN/m}^3$ . The artesian pressure is such that a casing through the clay into the sand has water rising 10 m above the top of the clay layer (ground surface). How deep can the excavation be dug into the clay to maintain a minimum factor of safety of 1.5 against bottom blowout failure?

**Solution 24.24**

The safe thickness  $h$  of the clay layer after excavation is:

$$h = \frac{\gamma_w h_w}{F\gamma} = \frac{9.81 \times 30}{1.5 \times 19} = 10.33 \text{ m}$$

Therefore, the safe excavation depth is  $20 - 10.33 = 9.67 \text{ m}$ .