CHAPTER XIV. SANITARY LANDFILL

A. Introduction

Left unmanaged and uncontrolled, solid wastes openly dumped on the land: 1) generate liquid and gaseous emissions (leachate and landfill gas) that can pollute the environment, and 2) represent a breeding ground for disease-bearing animals and microorganisms. Other risks to the public health and safety and to the environment are also posed by the uncontrolled land disposal of solid wastes.

Sanitary landfilling, which is the controlled disposal of waste on the land, is well suited to developing countries as a means of managing the disposal of wastes because of the flexibility and relative simplicity of the technology. Sanitary landfilling controls the exposure of the environment and humans to the detrimental effects of solid wastes placed on the land. Through sanitary landfilling, disposal is accomplished in a way such that contact between wastes and the environment is significantly reduced, and wastes are concentrated in a well defined area. The result is good control of landfill gas and leachate, and limited access of vectors (e.g., rodents, flies, etc.) to the wastes [1-3]. The practice of sanitary landfilling, however, should be adopted in accordance with other modern waste management strategies that emphasise waste reduction, recycling, and sustainable development.

Currently, the implementation and practice of sanitary landfilling are severely constrained in economically developing countries by the lack of reliable information specific to these countries, as well as by a shortage of capital and properly trained human resources. This chapter attempts to partially fulfil the need for information by including explanations and descriptions of technologies and procedures proven appropriate in practice. There are explanations of underlying principles and directions for putting the technologies into practice. The chapter provides basic information for designing and implementing a well engineered sanitary landfill. Emphasis is placed on technologies and operating practices that generally are available to, and compatible with, conditions in economically developing nations. The coverage is sufficiently broad to encompass the conditions that are characteristic of the relatively high levels of industrialisation that are found in many of the large metropolitan areas, as well as those that are characteristic of the conditions of the less industrialised communities, both large and small.

B. Basic principles

B1. DEFINITION

All definitions of “sanitary landfill” call for the isolation of the landfilled wastes from the environment until the wastes are rendered innocuous through the biological, chemical, and physical processes of nature. Major differences between the various definitions are in the degree of isolation and means of accomplishing it, as well as in the requirements for monitoring and closing the fill and in maintaining the fill after its active life. In industrialised nations, the degree of isolation required usually is much more complete than would be practical in developing nations. Not surprisingly, the means of accomplishing the high degree of isolation in developing nations are complex and expensive.

In order to be designated a sanitary landfill, a disposal site must meet the following three general but basic conditions: 1) compaction of the wastes, 2) daily covering of the wastes (with soil or other material) to remove them from the influence of the outside environment, and 3) control and prevention of negative impacts on the public health and on the environment (e.g., odours, contaminated water supplies, etc.). However, meeting all specific aspects may be technologically and economically impractical in many developing countries. Therefore, the short-term goal should be to meet the more important aspects to the extent possible under the existing set of technical and financial circumstances. The long-term goal should be to eventually meet all of the specific aspects of the design and operating conditions. Only when a fill meets all of the specific conditions will all of the benefits associated with a sanitary landfill be realised. The most important condition is the prevention of negative impacts on public health and the environment. The basic design and operating aspects of a sanitary landfill in terms of routes of impact outside the fill and of meeting the three basic conditions are illustrated in Figure XIV-1.

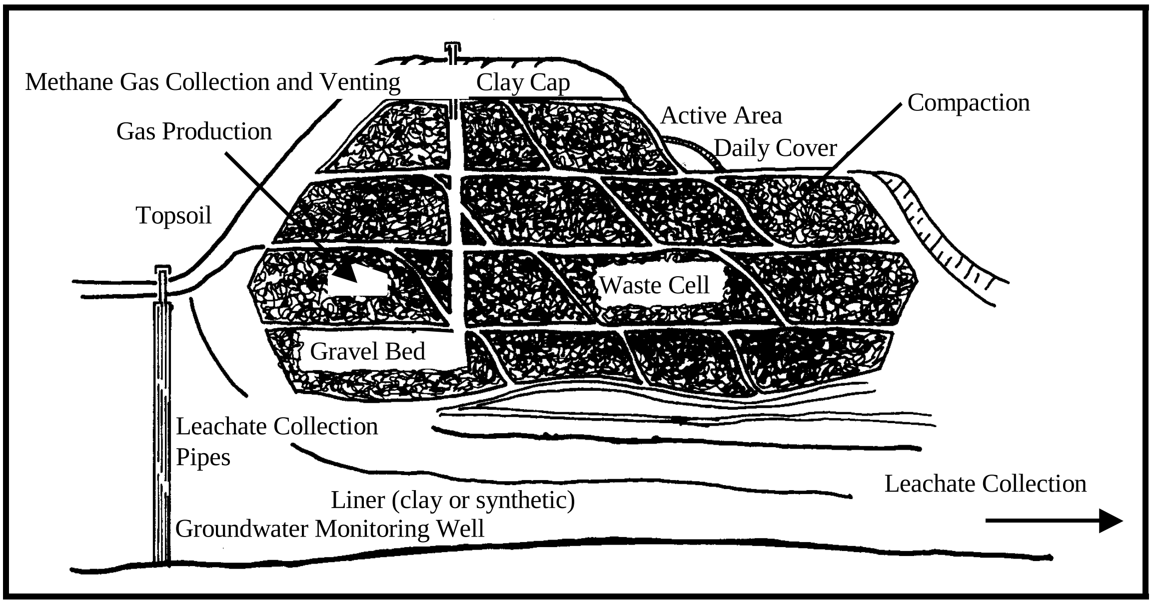


Figure XIV-1. Schematic diagram of basic aspects of a sanitary landfill

B2. PLANNING for a landfill

For this chapter, planning involves the collection of information on type, amount, generation rate, and characteristics of the wastes to be accepted for landfilling. Acquisition of this information is a prerequisite to rational design and efficient and effective development of a landfill. For example, knowledge of the composition of the waste stream destined for landfilling leads to an awareness of possible opportunities for recycling or reuse of certain constituents of the waste stream. Indeed, it should be noted that the underlying assumption is that reduction and recycling are the preferred courses of action, and that landfilling is indicated only when reduction and recycling are unfeasible, and is intended for the residue left after recycling.

C. Landfill processes

Physical, chemical, and biological processes are discussed in this section. Of the three types, the biological processes probably are the most significant. However, the biological processes are strongly influenced by the physical and chemical processes. The last part of this section considers some of the consequences of the three types of processes.

C1. PHYSICAL

In general, significant physical reactions in the fill are in one of three very broad forms: compression (compaction), dissolution, and sorption. Because settlement is an invariable accompaniment of compression, the two usually are discussed together. Similarly, dissolution and transport are closely associated phenomena, although not to the same degree as compression and settlement. All components of the buried fill are subjected to the three processes.

Compaction is an ongoing phenomenon that begins with compression and size reduction of particles by the compacting machinery and continues after the wastes are in place. The continuing compression is due to the weight of the wastes and that of the soil cover (burden). Sifting of soil and other fines is responsible for some consolidation. Settling of the completed fill is an end result of compression. This settling is in addition to the settlement brought about by other reactions (e.g., loss of mass due to chemical and biological decomposition).

The amount of water that enters a fill has an important bearing on physical reactions. Water acts as a medium for the dissolution of soluble substances and for the transport of unreacted materials. The unreacted materials consist of animate and inanimate particulates. Particle sizes range from colloidal to several millimetres in cross-section.

In a typical fill, the broad variety of components and particle sizes of the wastes provides conditions that lead to an extensive amount of adsorption, which is the adhesion of molecules to a surface. Of the physical phenomena, adsorption is one of the more important because it brings about the immobilisation of living and non-living substances that could pose a problem if allowed to reach the external environment. It could play an important part in the containment of viruses and pathogens and of some chemical compounds. Adsorption does have its limits, one of which is its questionable permanency. One or several factors can alter permanency. For example, it can be altered by the effect of biological and chemical decomposition on adsorption sites.

Absorption is another of the physical phenomena that takes place in a fill. It is significant in large part because it immobilises dissolved pollutants by immobilising the water that could transport them and suspended pollutant particulates out of the confines of the fill. Absorption is the process whereby substances are taken in by capillarity. Most of the absorption potential of landfilled municipal waste is attributable to its cellulosic content. However, it should be recognised that, excepting fills located in arid regions, eventually all absorbent material in a fill becomes saturated. Consequently, absorption may be regarded as being only a delaying action as far as pollutant release is concerned.

C2. CHEMICAL

Oxidation is one of the two major forms of chemical reaction in a fill. Obviously, the extent of the oxidation reactions is rather limited, inasmuch as the reactions depend upon the presence of oxygen trapped in the fill when the fill was made. Ferrous metals are the components likely to be most affected.

The second major form of chemical reaction includes the reactions that are due to the presence of organic acids and carbon dioxide (CO_2) synthesised in the biological processes and dissolved in water (H_2O). Reactions involving organic acids and dissolved CO_2 are typical acid-metal reactions. Products of these reactions are largely the metallic ions and salts in the liquid contents of the fill. The acids lead to the solubilization and, hence, mobilisation of materials that otherwise would not be sources of pollution. The dissolution of CO_2 in water deteriorates the quality of the water, especially in the presence of calcium and magnesium.

C3. BIOLOGICAL

The importance of biological reactions in a fill is due to the following two results of the reactions:

1. The organic fraction is rendered biologically stable and, as such, no longer constitutes a potential source of nuisances.

2. The conversion of a sizeable portion of the carbonaceous and proteinaceous materials into gas substantially reduces the mass and volume of the organic fraction.

At this point, it should be remembered that a fraction of the nutrient elements in the waste is transformed into microbial protoplasm. Eventually, this protoplasm will be subject to decomposition and, hence, it makes up a reservoir for breakdown in the future.

The wide variety of fill components that can be broken down biologically constitute the biodegradable organic fraction of MSW. This fraction includes the garbage fraction, paper and paper products, and "natural fibres" (fibrous material of plant or animal origin). Biological decomposition may take place either aerobically or anaerobically. Both modes come into play sequentially in a typical fill, in that the aerobic mode precedes the anaerobic mode. Although both modes are important, anaerobic decomposition exerts the greater and longer lasting influence in terms of associated fill characteristics.

C3.1. Aerobic decomposition

The greater part of decomposition that occurs directly after the wastes are buried is aerobic. It continues to be aerobic until all of the oxygen (O_2) in the interstitial air has been removed. The duration of the aerobic phase is quite brief and depends upon the degree of compaction of the wastes, as well as the moisture content since the moisture displaces air from the interstices. Microbes active during this phase include obligate as well as some facultative aerobes.

Because the ultimate end products of biological aerobic decomposition are "ash", CO_2, and H_2O, adverse environmental impact during the aerobic phase is minimal. Although intermediate breakdown products may be released, their amounts and contribution to pollution usually are small.

C3.2. Anaerobic decomposition

Because the oxygen supply in a landfill soon is depleted, most of the biodegradable organic matter eventually is subjected to anaerobic breakdown. This anaerobic decomposition is biologically much the same as that in the anaerobic digestion of sewage sludge. Microbial organisms responsible for anaerobic decomposition include both facultative and obligate anaerobes.

Unfortunately, the breakdown products of anaerobic decomposition can exert a highly unfavourable impact on the environment unless they are carefully managed. The products can be classified into two main groups: volatile organic acids and gases. Most of the acids are malodorous and of the short-chain fatty-acid type. In addition to chemical reactions with other components, the acids serve as substrates for methane-producing microbes.

The two principal gases formed are methane (CH_4) and CO_2. Gases in trace amounts are hydrogen sulphide (H_2S), hydrogen (H_2), and nitrogen (N_2). Landfill gas production, management, and recovery are discussed in another section.

C3.3. Environmental factors

The nature, rate, and extent of biological decomposition in a fill are greatly influenced by the environmental factors that affect all biological activities. The nature of biological decomposition determines the nature of the decomposition products. Among other things, rate determines the length of time during which the completed fill must be monitored and which must pass before the "reclaimed" area (i.e., completed fill) can be put to use -- whether it be for recreation, agriculture, construction, or other purposes.

One of the ways in which decomposition affects use of the completed fill is through its effect on the rate and amount of settlement (reduction in elevation), in that settlement is a major constraint on the use of the completed fill. Settling continues until biological decomposition has run its course. Therefore, the higher the rate of decomposition, the sooner the site can be put to use. Both research and demonstration studies have been performed over the past 5 to 10 years to accelerate biological decomposition of landfilled waste.

The principal factors that influence biological decomposition in a conventional fill are moisture, temperature, and the microbial nutrient content and degree of resistance of the waste to microbial attack. Moisture is a limiting factor in a fill at moisture content levels of 55% to 60% or lower, because microbial activity is increasingly inhibited as the moisture drops below the 55% level. For practical purposes, it ceases at 12%. Therefore, decomposition can be expected to proceed very slowly in fills located in arid regions.

The activity of most microbes increases with rise in temperature until a level of about 40°C is reached. For some types of microbes, the upper temperature is on the order of 55° to 65°C. Because temperatures in tropical regions are more favourable, decomposition can be expected to proceed more rapidly and to a greater extent in those regions.

With respect to nutrients, wastes characterised by a high percentage of putrescible matter approach the ideal in terms of decomposition. Among the wastes that fall into such a category are green crop debris, food preparation waste, marketplace produce waste, and animal and human manures. It is likely to find such a combination of ideal decomposition factors in developing countries in humid tropical regions of the world.

C4. IN-PLACE density and settlement

C4.1. Density

Representative densities of raw wastes are discussed in another section. Among the factors that determine or influence in-place density (i.e., density after the wastes have been deposited and compacted in the fill) are composition of the wastes and operational procedures. Progressive settlement of the entire mass of the fill occurs as a consequence of decomposition and weight of overburden.

Because of the effect of settlement, increase in density becomes a continuing phenomenon. The in-place density of a properly operated, relatively deep fill can be on the order of 900 kg/m^3; whereas that of a poorly compacted fill would be only about 300 kg/m^3. In the United States, the usual range of density directly after compaction is on the order of 475 to 712 kg/m^3 [31].

C4.2. Settlement

Settlement is manifested by a decrease in volume of the affected mass and subsequent reduction in elevation. For several reasons, the drop in elevation is not uniform throughout the fill. The lack of uniformity may be a serious constraint on the use of the completed fill. Undoubtedly, the greater the organic fraction and the deeper the fill, the greater will be the extent of settling. Rate of settling depends in large part upon that of the decomposition of the wastes and, hence, upon the factors that affect decomposition.

Because of the variations in the above factors and wide differences between operational procedures encountered in sanitary landfill practice, it is not surprising that a similarly wide variation exists between reported rates and the extent of settlement. Of the total settling, usually about 90% takes place during the first year [31]. In arid regions, settlement may be only 3% after three years, while that in subtropical regions may be as much as 20% after the first year. A.C. Cheney [32] indicates that whereas no physical settlement may occur if the initial density exceeds 1,060 kg/m^3, nevertheless a theoretical settlement of 40% due to waste decomposition is possible. However, he points out that with placement densities between 650 and 1,200 kg/m^3, annual rates of 0.55% to 4.7% have been measured.

D. Types of solid wastes

D1. SIGNIFICANCE of waste types

The type of solid waste to be disposed is an important consideration in the design of a sanitary landfill. Generally, sanitary landfills are considered to be land disposal facilities that receive solid wastes from residential, commercial, and industrial sources. The quantities and characteristics (e.g., composition, etc.) of the solid waste define the general procedures to be employed in the landfill operation. Furthermore, the type and composition of the wastes buried in the fill affect the quantity and composition of leachate generated and of the gases generated within the fill. Other considerations related to types of solid waste that affect the design and operation of landfills include the risks and hazards to personnel arising from the corrosivity, severe toxicity, or other dangerous property had by a particular waste.

D2. ACCEPTABLE wastes

Most solid wastes generated by residential, commercial, industrial, and agricultural sources may be disposed in a sanitary landfill of modern design without necessarily directly or indirectly endangering the well being of the public and the quality of the environment. For convenience of reference, such wastes are referred to as “acceptable wastes”. In contrast, many types of industrial process wastes (as opposed to the wastes generated in the offices of industrial facilities) should not be disposed in sanitary landfills but should be handled in specially designed landfills. These wastes are referred to as “unacceptable wastes”. Wastes that are unacceptable should receive special evaluation to assess the particular risks associated with their disposal.

With very few exceptions, only those wastes for which a given facility has been specifically designed should be accepted by that facility. An exception might be a waste that has been shown to fit within the existing or appropriately modified design capacity of the facility and that has the appropriate biochemical characteristics. Unfortunately, in many of the poorer developing nations, separation of wastes into acceptable and unacceptable categories is not practiced, nor is separation feasible in the foreseeable future. In many developing countries, circumstances are likely to be such that the only feasible course of action to gain some degree of control over land disposal is to accept all solid wastes without exception. The very act of removing the wastes from the open environment and placing them in a controlled land disposal facility would represent an advancement over the indiscriminate disposal practices currently in existence.

Dewatered solids (i.e., sludges or, synonymously, biosolids) from municipal wastewater treatment plants and water supply treatment plants (excepting raw sludge) can be regarded as being acceptable wastes.

D3. UNACCEPTABLE wastes

Ideally, the decision as to which wastes are to be deemed unacceptable should be made during the planning process, should be made jointly by the responsible governmental agency and the disposal site designer and operator, and should take into account the results of surveying large waste generators (in particular, industrial waste generators) in terms of the quantities and characteristics of their wastes. The wastes should be identified in the landfill development plans and frequent users of the disposal facility should be provided with a list of such wastes. Criteria recommended for use in decisions regarding acceptability should include the hydrogeology of the site; the chemical and biological characteristics of the waste; availability of alternative methods for disposal, reuse, or recycling; environmental risks; and the risks to the health and safety of the operating personnel and to the public.

Wastes that should require specific approval of the responsible government agency for acceptance at the disposal site should include those that are legally defined as “hazardous waste” or wastes that contain materials that are defined as “hazardous materials” -- medical wastes, bulk liquids and semi-liquids, sludges containing free moisture, highly flammable or volatile substances, raw animal manures, septic tank pumpings and raw sludge, and industrial process wastes. It should be noted that some animal wastes may be infectious because they contain animal disease organisms that can be transmitted to humans.

The United States Environmental Protection Agency (EPA) promulgated a definition of “hazardous waste” that is appropriate for industrialised and developing nations. According to the definition, a waste is hazardous if it poses a substantial present or potential hazard to human health or living organisms because: the waste is non-degradable or persistent in nature, it can be biologically magnified, it can be lethal, or it may otherwise cause or tend to cause detrimental cumulative effects [4].

D4. SPECIAL wastes

There are several types of wastes that are commonly termed “special wastes”, as previously introduced and discussed in Chapter II. Of these, medical (infectious) wastes and various types of sludges are commonly generated and disposed on the land in developing nations, and therefore, should receive special attention. Quantities of other types of special wastes will be considerably reduced through extensive scavenging and recycling activities characteristic of developing nations. Some of these wastes include institutional wastes, construction and demolition debris, animal manures, and animal carcasses.

E. Quantity and composition of the wastes

The need for conducting a reliable waste characterisation program (accurate determination of generation rates and composition) arises from the fact that rational planning and sound decision-making in solid waste management depends upon access to accurate and representative data regarding generation rates and composition. Unfortunately for planners and decision-makers, the quantity and composition of urban wastes vary not only from country to country, but also from city to city and even from neighbourhood to neighbourhood within a city [5,6].

Descriptions of the procedures that can be used to determine the quantity, composition, and other characteristics of the wastes are presented in Chapter III.

F. Site selection

F1. INTRODUCTION

The location and characteristics of the site will determine the extent and nature of the impact of a sanitary landfill on public health and the quality of the surrounding water, air, and land resources. Among the adverse effects that can be substantially limited or even avoided through proper siting of a fill are: 1) pollution of air, water, and soil resources with chemicals, gases, and organisms introduced or generated by landfilled wastes; and 2) a reduction of the aesthetic quality and monetary value of adjacent properties. Even with the best design, it is very difficult to completely isolate all natural resources from the contaminants and from the impacts that are mentioned in the following paragraphs. Since this is the case, selection of the best possible site becomes an extremely important matter. A prerequisite to the selection is the ability to determine which of the available sites most closely meets all criteria demanded by a "best possible site" [7]. Another factor that must be considered is the ownership and tenancy of land.

Site selection, particularly in the densely populated urban and suburban areas of industrialised countries, has become a highly contested socio-political process. A typical procedure for selecting a site either at the regional or local level in an industrialised country involves the identification of five to ten possible sites. This step is followed by a pre-feasibility analysis. The results of the analysis lead to the selection of two to five candidate sites. The next step of the process is to allow the public to comment on the sites. Finally, a decision is made and a site is selected. The process of selecting a landfill site in a developing country may be different from or a variant of that used by an industrialised country.

Despite the importance of selecting the best possible site, in many developing countries (and in many industrialised countries), most, if not all, choices are removed by pressures exerted on land use by an increasing population density, widening urban sprawl, and essential needs for food production and commerce. If these conditions are overbearing, the only feasible course is to locate sites remotely from urban centres and depend on the use of transfer stations. Obviously, if this course of action is taken, consideration must be given to the general trends and direction in population growth and to the means of transporting wastes from the area of generation to the remote disposal site.

Even though a set of unfavourable circumstances may prevent adherence to the criteria and parameters for the selection of the best possible site, knowledge of them is of substantial utility. For example, an awareness of the extent to which a site differs from the ideal is instructional for identifying protective measures to take against unfavourable impacts of land disposal at less than ideal sites. As a second example, if a fill must be installed on a hillside that has a body of water relatively close to its base, interception and diversion ditches can be dug between the fill and the body of water to divert runoff from the body of water.

Finally, as an essential part of the development of long-term land-use plans, the knowledge of siting criteria can be used when assigning future uses to land disposal sites [66].

Several factors that are fundamental to the selection of a site will be discussed in this section. Proper consideration of these will lead to the development of a disposal facility that will protect the quality of the groundwater and surface water resources, and of human life and habitation.

F2. USEFUL lifespan and area of site

Useful lifespan and area constitute the first of the factors and is determined by the following parameters: depth of the fill; quantity, rate of delivery, and characteristics of the solid waste; and operating practice. The site should be selected such that the useful life of the fill is sufficient to recover the capital investment. It is generally recommended that a landfill be designed for a useful lifespan of at least ten years. Determination of the size of the site must include two elements: gross area and useful fill area. Gross area is the total area within the property boundaries. Useful fill area excludes the area that will be taken up by buffers, access roads, and soil stockpiles. Useful fill area may be about 50% to 80% of the gross area. A diagram of a landfill is shown in Figure XIV-2. An indication of the usable land area required for one year of operation, as determined by population size and density of the compacted waste, may be gained from the curves plotted in Figures XIV-3 and XIV-4. Type of waste and operational procedures (including the amount of soil cover material) determine degree of compaction.

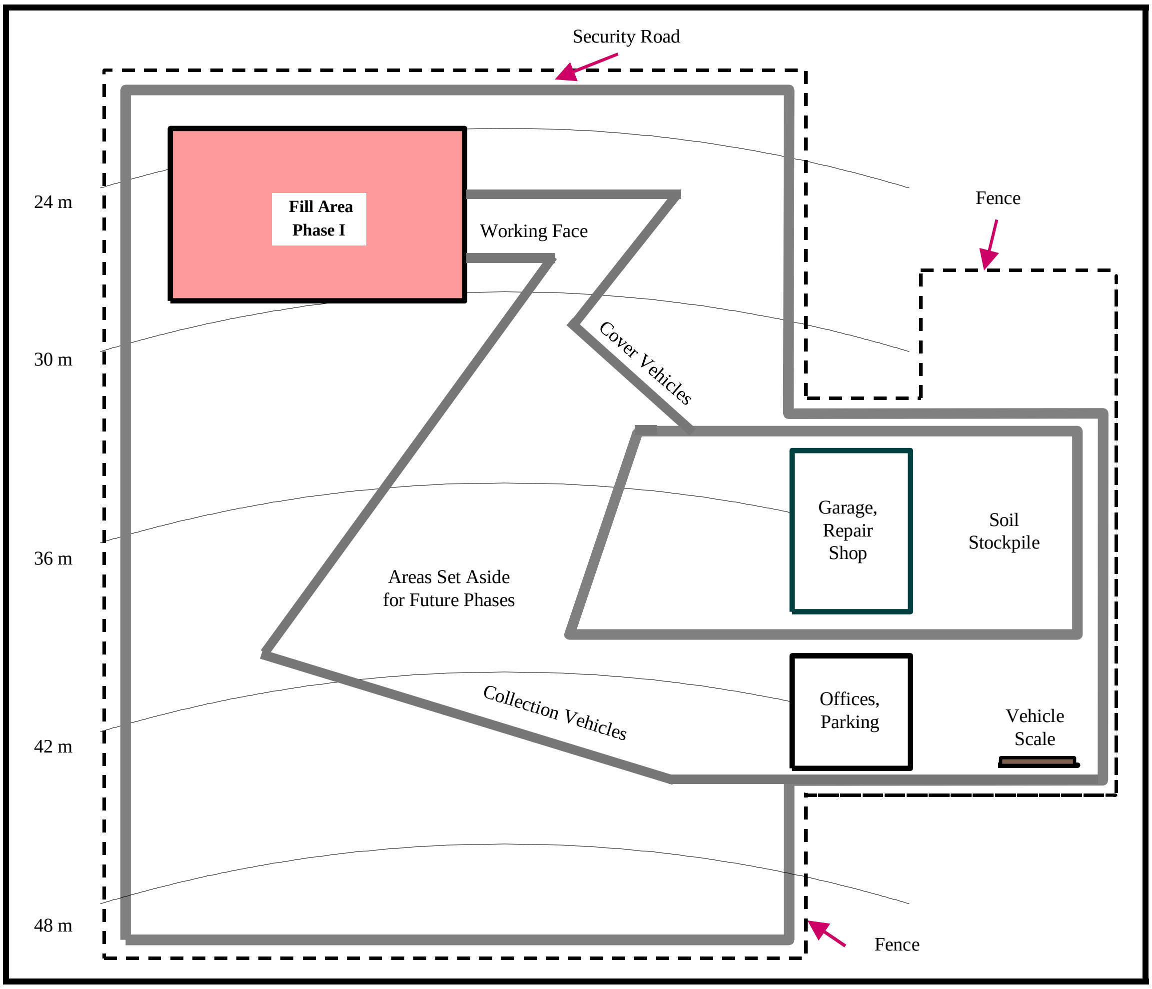


Figure XIV-2. Plan view of a landfill

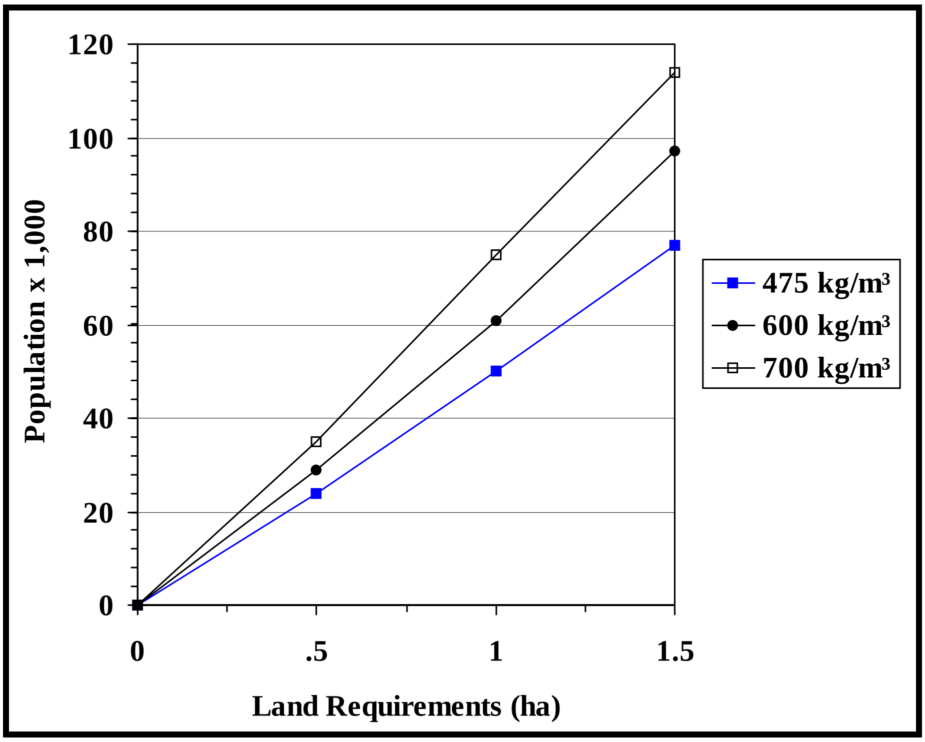


Figure XIV-3. Land requirements for a landfill as a function of compaction

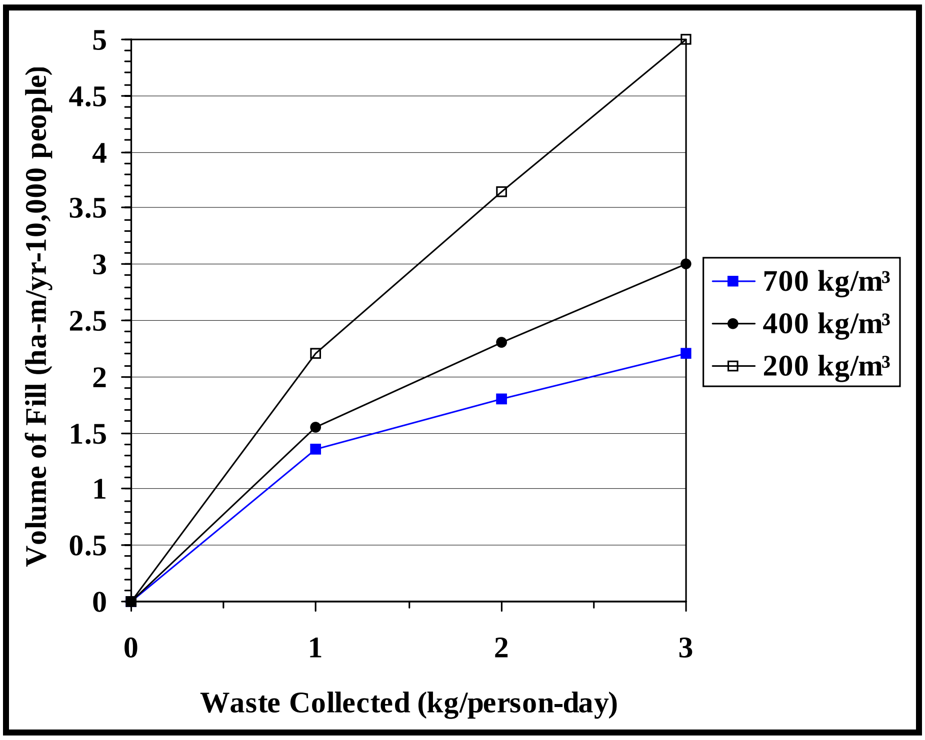


Figure XIV-4. Relationship between bulk density of waste and landfill volume required

The following formula can be used to calculate the useful life of a sanitary landfill:

$$L = \frac{V_T}{365(Q_P(1 + F_{Qs}))}$$

where:

- L = useful lifespan in years,
- V_T = volume of selected site in m^3,
- Q_p = quantity of solid wastes in m^3/day, and
- F_{Qs} = quantity of cover material expressed as a fraction of Q_p in m^3/day.

The quantity of waste can be projected using estimates of population. The estimate can be carried out by using the following formula:

$$Q_i = Q_p(1 + r)^n$$

where:

- Q_i = quantity of wastes to be collected in year "i",
- Q_p = present annual quantity of wastes collected,
- r = average annual growth rate in population as a decimal fraction, and
- n = number of years.

The surface area required for a particular volumetric capacity decreases as the depth of the landfill increases. The area requirements can be calculated by using the following formula:

$$A = \frac{V_T}{h}$$

where:

- A = area required in m^2,
- V_T = total volume of solid wastes and cover in m^3, and
- h = average depth of fill in meters.

Based on the formula and as depicted in Figure XIV-4, the compacted density of the wastes and soil have a substantial effect on the total volume and, therefore, on area requirements.

F3. TOPOGRAPHY

Regardless of type of site (e.g., abandoned coal strip mine, clay pit, natural depression), topographic information is a basic requirement in the development of an adequate facility design and determination of the impact of the facility. The importance of topography arises in part from the fact that precipitation will pond easily on a relatively flat site. On the other hand, it may erode an excessively steep site. In either case, operational difficulties are created. Slopes greater than 1% and less than 20% generally would be satisfactory. Topographic information is necessary in order to plan a surface water drainage system such that: 1) surface water is diverted around the fill area; and 2) runoff from the waste is prevented from damaging the environment. In addition, topographic information is required to accurately determine the capacity of the site and the type and extent of excavation required.

A topographic map of the facility should have sufficient contour intervals to clearly indicate surface water flow patterns in the general area and in each operational landfill unit. Topographic maps are available from a number of sources, or they may need to be developed using any of a variety of land surveying methods. Useful information that may be recorded on the topographic map includes:

- the 100-yr flood plain area,
- surface waters,
- current land use patterns (nearest households),
- water use wells,
- monitoring wells, and
- drainage or flood control barriers (dikes, levels).

Maps showing site topography before facility construction, during operation, and after closure should be prepared. All maps should be labelled with map scale, date, and orientation.

F4. SOILS

The availability of soil of proper characteristics for the construction of bottom liners, of cover systems, or both is usually one of the more important considerations when analysing and selecting a landfill site. An advantage is had if sufficient quantities are on the site or nearby to avoid the time and expense of securing synthetic materials or soils located remotely from the potential fill.

In the event that the site does not have sufficient quantity of the required types of soil, the materials must be imported to the site. If importation is necessary, the site should have enough space for soil storage. Sufficient soil should be stored to satisfy the needs for five to seven days.

Soil surrounding the fill influences contaminant migration and provides a foundation for facility structures. Important soil properties are: particle size distribution (gradation or texture); structure; strength; porosity; activity; depth; spatial distribution; quantity; liquefaction potential; relationships between moisture, density, and permeability; and workability.

The classification and analysis of properties of soils is a well established science. There are several classification schemes available. The most popular scheme is the Unified Soil Classification System (USCS). A listing of some of the USCS soil types is presented in Table XIV-1, along with some of their properties.

Table XIV-1. Some typical properties of soil classes

Soil Class	Description	Permeability (cm/sec)	Optimum Moisture Content (%)	Maximum Dry Density (kg/m^3)
GW	Same as GP (except well-graded in grain sizes)	$(2.7 \pm 1.3) \times 10^{-2}$	< 13.3	> 1908
GP	Gravel, very gravely sand (less than 5% silt and clay)	$(6.4 \pm 3.4) \times 10^{-2}$	< 12.4	> 1763
GM	Very gravely sand and loams	$> 3 \times 10^{-7}$	< 14.5	> 1827
GC	Very gravely loams and clays	$> 3 \times 10^{-7}$	< 14.7	> 1845
SW	Same as SP (except well-graded in grain sizes)	N/A	13.3 ± 2.5	1908 ± 80
SP	Sand, gravely sand (less than 20% very fine sand)	$> 1.5 \times 10^{-5}$	12.4 ± 1.0	1763 ± 32
SM	Loamy sand, sandy loam; sand; gravely sands and loams	$(7.5 \pm 4.8) \times 10^{-6}$	14.5 ± 0.4	1827 ± 16
SC	Sandy clay loam, sandy clay; gravely clay loams and clays	$(3 \pm 2) \times 10^{-7}$	14.7 ± 0.4	1845 ± 16
ML	Silt, silt loam, loam, sandy loam	$(5.9 \pm 2.3) \times 10^{-7}$	19.2 ± 0.7	1651 ± 16
CL	Silty clay loam, clay loam, sandy clay	$(8 \pm 3) \times 10^{-8}$	17.3 ± 0.3	1731 ± 16
OL	Mucky loams	N/A	N/A	N/A
MH	Silt, silty loam	$(1.6 \pm 1) \times 10^{-7}$	36.3 ± 3.2	1314 ± 64
CH	Silty clay, clay	$(5 \pm 5) \times 10^{-8}$	25.5 ± 1.2	1507 ± 32
OH	Mucky silty clay	N/A	N/A	N/A

Source: Reference 4.

Information regarding the strength of soils that serve as foundation for overlying facility components is required. Information is needed regarding the site's soil permeability (hydraulic conductivity -- usually in units of cm/sec) since landfill design must consider seepage through the foundation.

For economic reasons, onsite soils should be used for soil liner construction, cover material, and drainage layers to the extent permitted by the quantity and characteristics of the available soils and as required by the general conditions of the site. The volume of soil available on a given site is a function of site topography, groundwater depth, depth of trench excavations, ultimate height of the fills, and properties of the soils. In the United States, volume required for cover purposes generally ranges from 1 part soil for every 3 to 8 parts waste by volume. For small landfills, the ratio may be as high as 1 part soil to 1 part waste.

Two major considerations for using onsite soil are the ease with which the soil can be excavated and the seasonal variations in workability (e.g., clay-like silt when dry, moist, or frozen). Regarding engineering properties, well drained soils are suitable for drainage layers in leachate collection systems. Highly organic soils are generally unsuitable for most land disposal applications due to their low strength and poor workability. An exception might be the use of compost as daily cover material.

If a bottom liner is required by the landfill design, the availability of suitable soil on the landfill site is a substantial benefit. In general, the preferable soil is one with a permeability of less than 1 x 10^{-6} cm/sec when placed as the liner.

Three types of cover systems are usually employed in the construction of a sanitary landfill: daily, intermediate, and final. As in the case of bottom liners, the availability of suitable soils on the potential landfill site for the construction of the cover systems is beneficial and should be a major consideration when analysing potential sites. The characteristics that are suitable for the various cover systems are described later in this chapter.

F5. GEOLOGY

Information on the geology of a site is required for properly engineering a facility. Such information serves three important purposes: 1) identification of geological hazards, 2) provision of information for facility design, and 3) assessment of vulnerability of the site to groundwater contamination due to the hydrogeology of the site.

Much of the useful geological information for engineering purposes relates to bedrock -- namely, depth to bedrock, bedrock characteristics, and condition of the bedrock. This information is especially useful if bedrock is at or near the surface and will serve as part of the foundation for the facility.

The status of the bedrock has an impact on its stability as a foundation. Joints and other discontinuities can provide hydraulic conduits and constitute pathways for migration of contaminants. In the case that the fill has a synthetic liner (which is unlikely in most developing countries), when the water table is high, these pathways may result on localised hydraulic pressures or gradients on the liner.

Geological information is difficult to acquire when an unstable terrain is involved. The integrity of the structures on unstable terrain is especially vulnerable to natural or man-induced forces, such as floods, seismic displacement and deformation, volcanic activity, landslides, subsidence, and weak or unstable soils.

F6. HYDROGEOLOGY

The potential to pollute the groundwater at the landfill depends, to a considerable extent, on the hydrogeological characteristics of the site, such as:

- depths to groundwater,
- nature and approximate thickness of water-bearing formations or aquifers near the landfill,
- quality of the groundwater upgradient of the landfill,
- site topography and soil type,
- soil infiltration rates at the site,
- effects of nearby pumping wells on groundwater beneath the site,

- hydraulic conductivity and its distribution at and near the site,
- depth and nature of bedrock,
- horizontal and vertical components of groundwater gradients, and
- groundwater velocity and direction.

In an economically developing country, the determination of all of the relevant hydrogeological characteristics of a site may be an extremely difficult task. However, some of the data may be available from government records, surveys, and maps. If these records do not exist, the geology of the site will provide some information as to its hydrogeology. Other data may be collected by interviewing local residents about floods (duration, levels, year, etc.).

The assessment of hydrogeology should include classification of the groundwater underlying the site, determining level and direction of flow, and evaluating the potential for groundwater contamination. Pollution potential largely depends upon the extent to which the characteristics of the site will control contamination of groundwater by the disposed solid wastes. Obviously, if more than one site is available, the preferable site should be the one with characteristics that would most impede groundwater contamination. Any problems with the level of isolation of the wastes from the groundwater should be compensated by protective measures (such as installation of liners and initiation of groundwater quality monitoring), to the extent permitted by available local economic, technological, and human resources.

Some of the most important characteristics associated with the obstruction of groundwater contamination include surface and subsurface hydrogeologic conditions. These conditions determine the potential migration velocity of contaminants at the site. Some of the conditions are: physiographic setting, location of groundwater recharge areas, characteristics of the unsaturated zone, characteristics of the uppermost aquifer, and depth of confining beds.

F7. PHYSIOGRAPHIC setting

The physiographic setting is a combination of climate, topography, stream density, and geological structures.

Climate plays an important role on the design and operation of a landfill because of its impact on the amount of rainwater that may infiltrate through the unsaturated zone and into a groundwater system. Degree of infiltration depends upon the amount of precipitation, volume of surface ponding and runoff, and the rate of evapotranspiration. Ambient temperature and relative humidity also have an impact on infiltration, evaporation, and evapotranspiration. The potential for groundwater contamination from a well designed and constructed landfill in arid and semi-arid regions can be quite low. In the case of semi-arid and arid regions (annual precipitation lower than about 10 cm), it may not be necessary to install a bottom liner or, consequently, leachate management facilities. On the other hand, the potential is quite high in humid regions. The amount of rainfall, as well as the timing and intensity, are very important considerations. For example, if rainfall is seasonal, the amount of rainfall during the wet season may be of such magnitude as to allow significant infiltration even though the annual average rainfall may be relatively low.

The tendency of precipitation to accumulate on flat sites and to erode on steep sites generally limits the siting of landfills to areas that have a natural slope of more than 1%, but less than 20%. In general, high topographic relief areas are less desirable for landfill siting than low relief areas.

The preference is due to the potential for rapid contaminant transport in the subsurface and rapid water flow on the ground surface.

In an area in which streams are relatively close together, the potential of surface water contamination increases in locations in which an unusually short underground flow path precedes discharge of contaminants into a stream. However, the overall extent of any groundwater contamination may be limited by nearby discharge points. The risk of surface water contamination in areas of low stream density may be reduced due to attenuation of the contaminants by subsurface media. On the other hand, widely spaced streams may also lead to the development of larger and longer term groundwater contamination zones. However, the increased attenuation potential and reduced risk of surface water contamination associated with low stream densities override the drawbacks of a large potential groundwater contamination area. In summary, the general preference is to select sites characterised by low stream densities [8].

F8. GEOLOGY and soil characteristics

Knowledge of the geological structure and history of an area is needed to predict groundwater behavioural characteristics. If sedimentary units are present or suspected, knowledge of the depositional history of the region may reveal unsuspected discontinuities in apparently uniform units (e.g., permeable channel deposit in a low permeability unit).

Permeability of the surrounding rocks and soils is an important factor in evaluating the suitability of an area as a potential site for a landfill. Although the primary permeability of a soil formation generally refers to groundwater intergranular flow (flow along the primary porosity), rate and direction of flow are controlled by the flow along fractures, joints, bedding planes, and solution cavities (secondary porosity). Secondary porosity may prevail when subsurface flow takes place in carbonate terrains, metamorphic and igneous rocks, and folded and faulted sedimentary rocks. Short circuiting may occur in situations in which secondary porosity is prevalent, inasmuch as low permeability (secondary porosity) is less an obstacle to contamination than is high permeability (primary porosity).

Unless control measures such as liners and leachate collection systems are implemented, a high permeability near the ground surface allows contaminants to move relatively quickly to the groundwater. Conversely, contaminants move slowly due to low permeability near the surface. Consequently, more time is allowed for attenuation or for instituting remedial measures before the groundwater becomes extensively contaminated. However, in such a situation, runoff of contaminated water may increase surface and subsurface water contamination.

F8.1. Groundwater recharge

The potential for groundwater recharge to significant aquifers is one of the most important considerations in the evaluation of a potential landfill site [29]. Areas of natural recharge must be avoided. Accordingly, the location of a site with respect to a regional groundwater flow system must be defined, particularly if the site is in or close to a primary recharge area. The introduction of contaminants in certain recharge areas may bring about migration of a contaminant over considerable distance and long residence times for a contaminant within the aquifer before reaching a discharge area.

Recharge areas are usually in topographically high areas where the water table may be relatively deep. Conversely, the water table is either near or at the land surface in discharge areas. Because of a decrease in potential energy with depth, the flow component is primarily downward in upland recharge areas; whereas, upward flow is the usual course in surrounding lowland discharge areas. The groundwater flow may be mostly horizontal in locations between the major recharge and discharge areas in laterally extensive regional flow systems. Moreover, significant recharge can take place between the major recharge and discharge areas. Finally, an adequate prediction of pathways of contaminant migration and determination of the recharge potential to underlying aquifers presupposes the making of an assessment of vertical gradients at the site under consideration.

The soil infiltration potential should be evaluated on a site-specific basis. Doing so may involve making determinations of the unsaturated hydraulic activity of the soil, particularly the soil that separates the bottom of the landfill from the uppermost aquifer. Such determinations are useful in determining the protective potential of the site against groundwater contamination by a landfill.

F8.2. Vadose zone

The vadose zone is the zone that lies between the surface of the land and the principal water table (Figure XIV-5). Although the vadose zone is generally known as the “unsaturated zone”, saturated regions may be found in some vadose zones. Examples of such regions are perched water tables and tension-saturated zones. Vadose zone characteristics are important in arid regions because the water table may be located fairly deeply in those regions. Characteristics are less important in vadose zones in humid regions where the water table is shallow or in areas where fractured rock media occur near the ground surface.

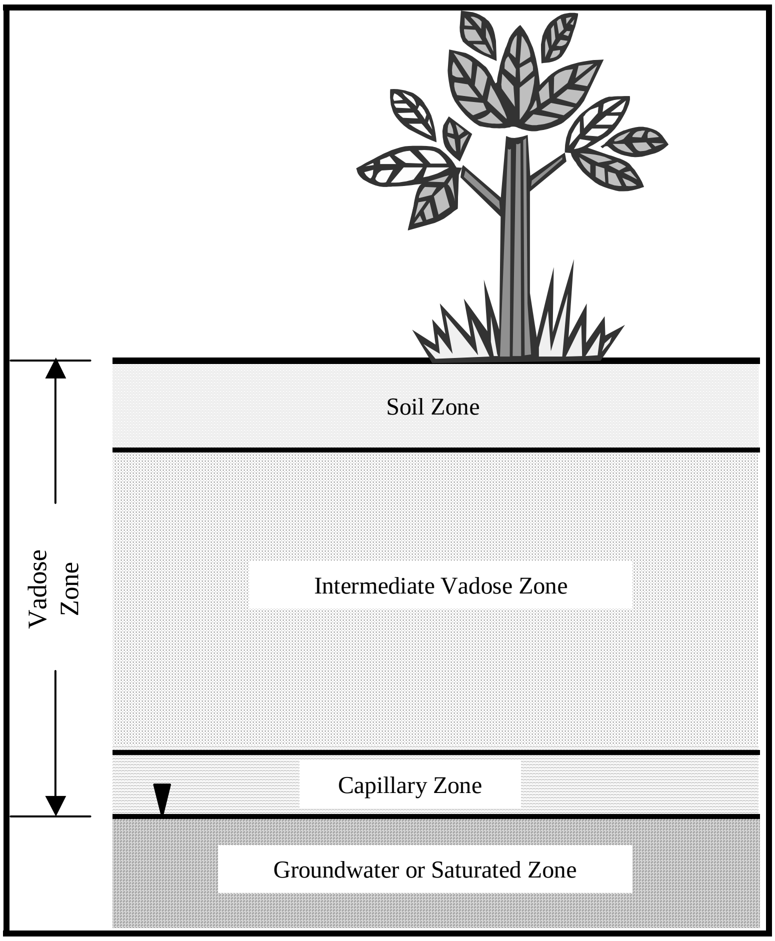


Figure XIV-5. Diagrammatic sketch of vadose and groundwater zones

Among the physical, chemical, and microbiological characteristics of the vadose zone that have a bearing on the mobility, attenuation, or degradation of contaminants in the subsurface are:

- mineralogy,
- porosity,
- organic matter content,
- particle size distribution,
- soil horizons and structure,
- soilwater characteristics,
- cation exchange capacity,
- temperature,
- soil pH, and
- availability of microorganisms.

A vadose zone that offers substantial protection against groundwater contamination should have the following characteristics: substantial thickness, a large capacity for adsorption and degradation of potential pollutants, a uniform soil structure, and consisting of a material characterised by low hydraulic conductivity.

The large sorption capacity of strata containing clay-rich soils is counterbalanced by the tendency of contaminants to move around them rather than through them. This tendency minimises the attenuation potential that may come from the presence of such strata. On the other hand, poor sorption materials (sands) are usually very permeable.

F8.3. Uppermost aquifer

The term "aquifer" refers to a geological formation in which the amount of saturated permeable material is sufficient to result in a significant amount of water in wells and springs. An aquifer is classified as a "confined aquifer" if its top is covered by an impermeable layer. If the top of the water table represents the top of the aquifer, such an aquifer is classified as "unconfined".

The uppermost aquifer should be carefully monitored because it is the portion of the saturated zone that has the highest probability to be contaminated. It may be confined or unconfined. Certain uppermost aquifers may not represent a threat to groundwater quality, for example, those that do not have underlying aquifers, are not used for water supply, contain sorptive materials to attenuate potential contaminants, are deep, and are under a vadose zone that contains sorptive materials.

F8.4. Underlying aquifers

The occurrence, characteristics, and usage of sources of groundwater that may underlie uppermost aquifers are factors to be considered in evaluating the potential of a landfill to contaminate groundwater. Considerations discussed for uppermost aquifers are applicable to underlying aquifers. Factors of particular importance are type of existing and potential usage, flow components, ambient water conditions, and the thickness and properties of materials that separate the aquifers. Among the factors that are the more effective in the prevention of contamination of groundwater resources are aquifers that are separated by a very thick layer of low permeability, sorptive materials or that lack direct hydraulic connections with the uppermost aquifer.

F8.5. Summary of relationship between geological and hydrogeologic characteristics and groundwater contamination

The combination of characteristics that would limit the risk of groundwater contamination is the following:

- The distance between the ground surface and the surface of the water in an unconfined aquifer or the top of a confined aquifer is greater than 30 m.
- The net recharge rate is less than 5 cm/yr.
- The water bearing unit is massive, dense, and unfractured.
- The soils are moderately hard or impervious.
- The topographic gradient is steeper than 18%.
- The vadose zone is comprised of dense, impervious media.
- The hydraulic conductivity for the water-bearing unit is less than about 0.4 m^3/day/m^2.

The greatest risk of groundwater contamination would be represented by the existence of the following set of conditions:

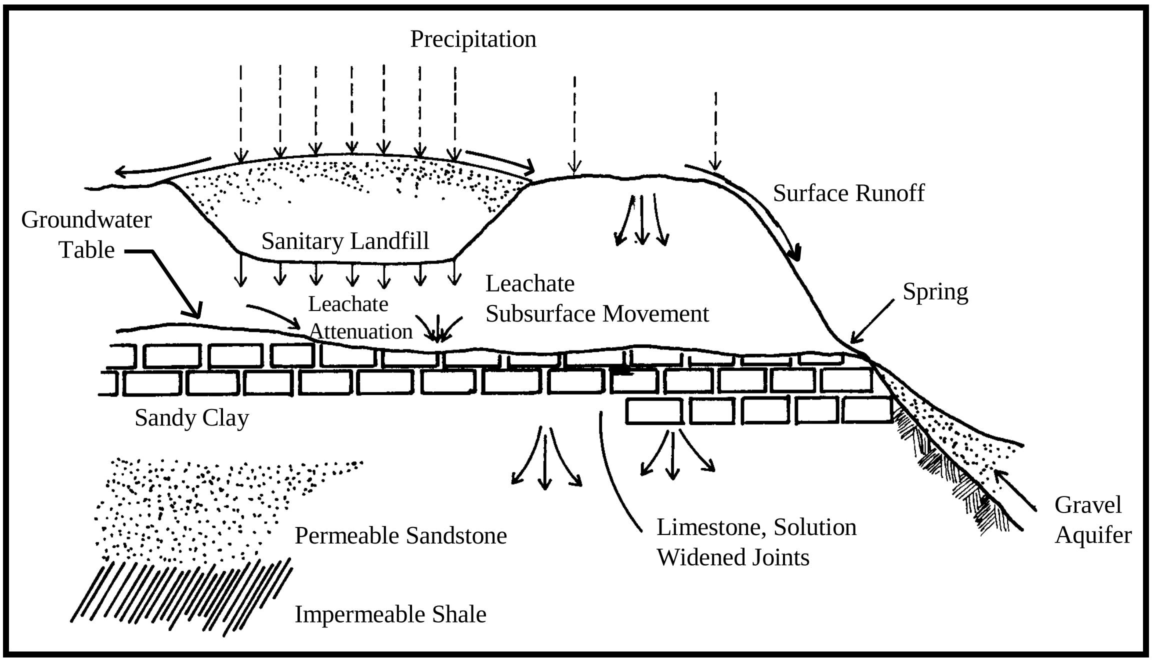
- The depth from ground surface to the water table is less than about 3 m.
- The groundwater recharge is greater than 25 cm/yr.
- The aquifers and vadose zones consist of irregular limestone or fractured basalt.
- The topographic gradient is less than 2%.
- The hydraulic conductivity is greater than about 80 m^3/day/m^2.

A fairly concise grasp of the interrelation between the various geologic and hydrogeologic factors, direction of leachate travel, and contamination of water resources may be gained from a review of Figure XIV-6.

F9. VEGETATION

Vegetation of concern ranges from the native types growing at the site to types planted as a part of site preparation and maintenance. The types of vegetation include small trees, shrubbery, herbaceous annuals, perennials, and groundcovers.

Trees and shrubs are planted to serve as a buffer; to reduce dust, noise, door, and visibility problems; and for site beautification. A groundcover reduces or even eliminates wind and rain erosion of the landfill cover, improves aesthetic quality, and enhances moisture removal by way of evapotranspiration. The amount of water removed through evapotranspiration is significant. A groundcover is especially important because of its role in ensuring the long-term stability and performance of the final landfill cover system.



Source: Reference 31.

Figure XIV-6. Interrelation between climatic, topographic, hydrologic, and geologic factors in terms of leachate travel and groundwater contamination

F10. SITE access and transport

The cost of transport of waste to a potential site should be an important consideration during the process of identifying a location for a disposal site. If this were the sole consideration, the optimum location would be one located at the centroid of the waste collection area. However, other considerations come into play, some of which may override the hauling cost consideration. One such consideration is the decline in availability of land due to the constantly strengthening competition exerted by other uses. Socio-political considerations and environmental concerns also are important elements of the site selection process. The competing considerations could be such that the siting of the fill may be so distant that a transfer station would be required.

The conditions of the roads leading to the landfill have an impact on the cost of the overall system. Poor access both delays travel and damages vehicles. Thus, access to the site should preferably be over paved roads or all-weather unpaved roads. In the case of the use of trailer trucks to transport the wastes, the roads, bridges, and similar structures should be adequately designed to support the loads.

F11. LAND use

Land use involves two considerations during the site selection process: 1) compatibility of use of the site for the landfill with the present and future uses of adjoining land areas, and 2) availability of soil for necessary cover material (discussed previously).

Regardless of the state of a country's economic development, availability of the site selected for landfill depends to a large extent upon governmental and public acceptance. Hence, the degree of compatibility of the intended fill with the uses intended for surrounding land areas has important social and political implications.

A landfill places land use constraints not only upon the fill itself before, during, and after its completion, but also upon the use of the surrounding area. The constraints usually are determined from due consideration of technical issues, land use compatibilities, and public policy. The constraints should not be so severe that the satisfactory integration of the fill into the area's master plan is prevented. Social and political overtones come into play when it becomes necessary to convince the public that the integration can and will be made.

The future use of the surrounding area also has an important bearing upon the design and operation of the fill. For example, it determines the amount of wastes that the fill must accommodate and, consequently, it establishes the capacity required of the site. It also places constraints upon the nature of the waste that could be disposed at the site. Future use and location have an impact on the final shape, height, and contour of the fill.

On the other hand, proper siting of a landfill, including the construction of suitable access roads, has the tendency to attract the development of low-income housing. Thus, adequate measures must be taken to restrict intrusion into and around the site.

F12. ECONOMIC considerations in site selection

The cost of cover materials depends in large part upon the availability of the materials. The cost would be minimal if the material could be obtained from the site itself. If not, then the purchase price of the material, plus the cost of transporting it to the site, could have a substantial effect on the total costs of disposal. The high cost associated with securing the cover material and transporting it to the site, in many cases, prevents many communities in economically developing countries from covering the wastes on a daily (or relatively frequent) basis.

Hauling costs for transporting the wastes from the collection point to the landfill are a major consideration in selecting a landfill location. Obviously, the further the fill is from the centroid of the collection area, the greater the hauling costs. In fact, the distance between the site and the point of generation can be so great that the hauling costs exceed those of land and pre-development.

The decision regarding a feasible distance to the disposal site should be determined by the costs and the benefits that may be associated with distance. For instance, a site that happens to be farthest away from the collection points may also have the lowest potential for exerting an adverse impact upon the public health and the quality of air, water, and land resources. The decision with regard to a feasible distance will generally rest upon what is perceived as being the more important: lower costs of hauling and degraded resources, or higher costs and higher quality of health and natural resources. At issue is the willingness of a community to pay to improve the quality of life. Of course, distance brings another possibility -- namely, effect of distance on the cost of the land occupied by the site and impact upon public health and quality of the environment. Distance may lower land costs in addition to lessening the extent of adverse impact upon public health and environmental quality.

F13. DECISION-MAKING process

A suggested decision-making process for selecting a suitable landfill site in an economically developing country involves three steps:

1. The first step is to make an initial assessment of potential sites by doing the following:

   - determining physical and demographic limitations;

- establishing suitable study areas on the basis of haul distance, topography, geology, and surface and groundwater conditions;

- identifying candidate sites;

- assessing financial feasibility on bases of haul distances, approximate site development costs, and operating hours per week for equipment and personnel;

- performing preliminary site investigations as to location, land use, haul distance and routes, topography, hydrogeology, soil characteristics, and area of the site; and

- eliminating undesirable sites.

An approach that takes into consideration the elements of step-1 involves the use of a computerised database that describes the physical, sociological, and demographic data within a physical area. Development of the information is by way of digitising various types of maps (e.g., land use, geographical structure, census tract) and adding other demographic data.

2. The second step in the process is to screen the candidate sites. This step is composed of the following:

- investigating four to five candidate sites and identifying site-specific problems;

- evaluating and ranking sites; and

- obtaining public input.

3. The third step consists of:

- preparing a preliminary design for each site so that capital and operating costs can be estimated;

- determining and evaluating the use upon completion of each of the sites;

- evaluating the costs associated with developing and operating each site, including the cost of hauling wastes to the site;

- selecting a site and listing alternative sites; and

- acquiring the site.

G. Landfill technology

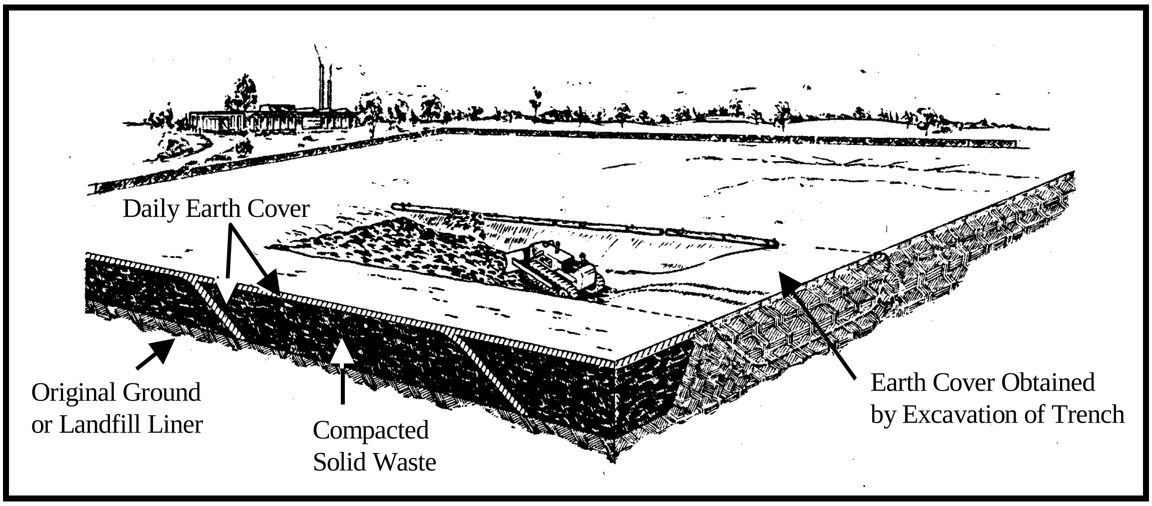
G1. INTRODUCTION

Landfill technology applies to a variety of aspects of the construction and operation of the landfill facility. Consequently, in this section, topics discussed include not only practices of disposal, e.g., formation of the cellular structure of the sanitary landfill, but also some other aspects of technical importance. Some of the other aspects are the liner and cover as landfill system components and the special circumstances that must be taken into account concerning the different types of wastes that can be expected to be delivered to a disposal facility in developing countries. Also, the role of technology in the construction and use of the completed fill is discussed.

G2. CELL design and construction

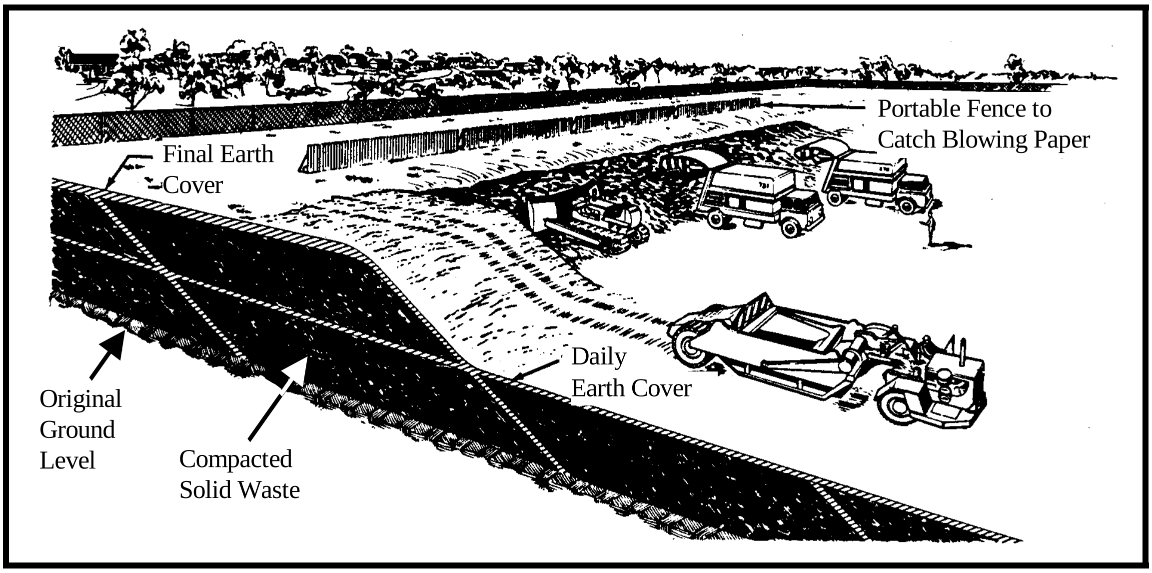
Experience has shown that no one method of landfilling is best for all sites, and a single method is not necessarily the optimum for any given site. Selection of a method depends upon the physical condition of the site, amount and types of solid waste to be disposed, and the relative costs of the various options. The two basic types of landfill methods are the trench (Figure XIV-7) and the area (Figure XIV-8). The trench method is best suited for sites that have a flat or gently rolling land surface, a low groundwater table, and a soil layer thicker than 2 m.

The area method is applicable with most topographies and probably would be the better of the two choices for sites that receive large quantities of solid waste. A design using a combination of the two methods may be the most appropriate approach at some sites.



Source: Reference 11.

Figure XIV-7. Trench method of sanitary landfilling



Source: Reference 11.

Figure XIV-8. Area landfill

All true sanitary landfills consist of elements known as "cells" (Figure XIV-9). A cell is built by spreading and compacting the solid waste into layers within a confined area. At the end of each working day, or during the working day as well, the compacted refuse is covered completely (including the working face) with a thin, continuous layer of soil. The soil cover also is compacted. The compacted waste and its daily soil cover make up a cell (Figure XIV-9). A series of adjoining cells at the same elevation constitute a “lift”. A completed fill may consist of one or several lifts.

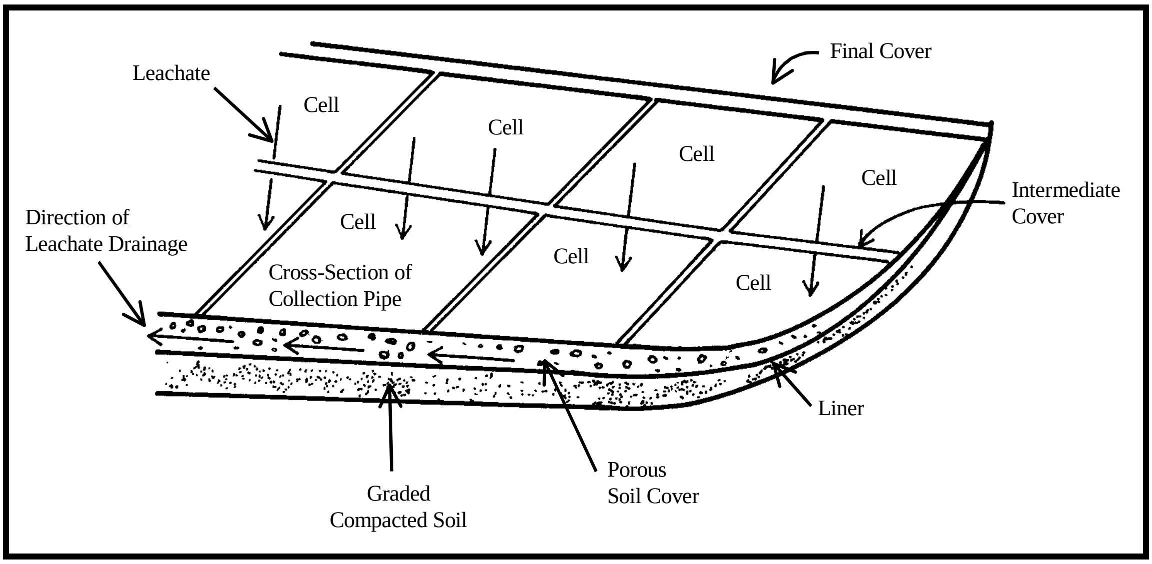


Figure XIV-9. “Cellular” structure of a landfill

The cells are designed based on the quantity of wastes requiring disposal. The basic elements of a cell are: height, length, width of working face, slope of sidewalls, and thickness of daily cover. The height of a cell is a function of the quantity of waste, thickness of daily cover, stability of slopes, and degree of compaction. Typical heights vary between 2 and 4 m.

The minimum width of the cell or minimum width of the working face depends upon the type of equipment used. It is generally recommended that the minimum width of the cell be about 2 to 2.5 times the width of the blade used for building the cell. The minimum recommended cell widths based on rate of waste delivery are: 8 m for up to 50 Mg/day, 10 m for 51 to 100 Mg/day, 12 m for 101 to 225 Mg/day, and 15 m for 226 to 500 Mg/day.

The width of the working face also is dictated by the maximum number of vehicles arriving at the disposal site at the peak hour. The width of the working face (in meters) can be calculated by multiplying the maximum number of vehicles arriving at the peak hour by about 4.

The width of the working face is one of the major weaknesses in the operation of a land disposal facility in economically developing countries. Generally, the working face is excessively wide in order to accommodate the maximum number of vehicles and to avoid long delays. However, the width is such that it is extremely difficult to achieve any type of control. In practice, one should attempt to operate a landfill using the smallest practical area for the working face.

The slope of the cell is the inclined plane upon which the wastes are distributed. The maximum recommended slope is 1 to 3 (vertical to horizontal). Slopes less than about 1 to 6 result in an undesirably large area for the working face.

The trench method has only one working face. On the other hand, the area and combined methods may have two working faces.

G2.1. Trench

The trench method involves the excavation of a trench. Once the excavation is completed, the waste is placed into the trench, spread, and compacted (Figure XIV-7). The waste is deposited on the slope of the trench. The excavated soil serves as cover material. Soil not used for the daily cover is stockpiled for later use in a subsequent area that might be constructed on top of the completed trench fill.

The stability of the sidewall is a critical factor in the design of a trench landfill. Sidewall stability is a function of the characteristic strength of the soil, depth of the trench, distance between trenches, and slope of the sidewall. Maximum depth and steepness of sidewall slope are compatible with clays, glacial till, or other fine-grained, well-graded, consolidated soils. Weaker soils require gentler sidewall slopes. Other factors that may affect soil stability and permissible steepness of sidewall slope are climatic conditions and the length of time the trench is to remain open.

Because a suitable distance should be maintained between the bottom of the fill and the groundwater table, compatibility with groundwater protection places another constraint on trench depth.

Theoretically, the trench should be as narrow as possible since the amount of required cover material is a function of the width of the trench. However, because width must be sufficient to allow discharge of the wastes as well as accommodate the compaction equipment, practicality demands that the trench be wide enough to accommodate the number and types of vehicles that use the fill. Generally, the indicated width is twice that of the largest piece of equipment that will work in the trench.

Based on the projected size of the landfill, excavation may either be done continuously at a rate adjusted to landfilling requirements, or periodically on a contract basis.

The direction of the prevailing wind should be taken into consideration in the alignment of the trenches since wind exerts a significant influence on the amount of blowing litter. The most effective alignment in terms of reduction of amount of blowing litter is one that is perpendicular to the prevailing wind.

To ensure proper drainage, the bottom of the trench should be sloped away from the active fill area. Water that accumulates at the bottom of the trench should be pumped out of the trench. Surface water can be diverted from the trench by constructing temporary berms on the sides of the excavation.

G2.2. Area

As opposed to the trench method, the area method does not involve excavation of trenches (Figure XIV-8). Instead, a layer of waste is spread and compacted on the surface of the ground (on the inclined slope). Cover material is then spread and compacted over the layer of waste. The area method should be used on flat and gently sloping land. This method can be adapted to quarries, strip mines, ravines, valleys, canyons or other land depressions, and excavations made for the landfill.

G2.3. Ramp

The ramp, also known as the progressive slope method, consists of spreading and compacting the solid waste on a slope. The ramp method is similar to the area method. However, in a departure from the area method, cover material is obtained from the soil surface immediately in front of the working face -- thus, leaving a slight depression to begin receiving deliveries of waste the following day. Because it does not involve the importation of cover, the ramp method promotes greater efficiency of site usage when a single lift is constructed.

G2.4. Combination of fill methods

The area method and the trench method might be used in the same site if the particular site has varying thicknesses of topsoil and receives a large amount of wastes. The trench method would be used in situations where the topsoil layer is thickest. Soil not used for cover on the trench fill would be stockpiled for the area fill. Through the use of the area method and stockpiled cover material, additional lifts can be constructed upon a completed lift.

G2.5. Slope stability

The stability of slopes of wastes and of waste/bottom liner interfaces in the landfill are important in managing the fill cost effectively and in protecting the safety of landfill workers and other people that reside on or near the fill. Sloughing or landslides of waste can occur in improperly constructed masses of waste that have steep slopes. When the quantities of waste are large and slope failure occurs, the movement of waste can destroy property, cause personal injury or death, and (further) contaminate or disrupt the environment, or a combination of these. Uncontrolled disposal of waste on land is obviously susceptible to slope instability, particularly in the case where large quantities of waste have been dumped indiscriminately over a ledge or into a ravine. However, engineered landfills are also susceptible to slope failures unless designed properly. Substantial slope failures in waste disposal sites have occurred in the United States [86], the Philippines, Turkey, Colombia, and Italy [85], among others. Events that can trigger movement of an unstable slope of waste include, but are not limited to, earthquakes and heavy rainfall.

The design and construction of the slopes of landfill cells and of completed landforms must take into consideration the types and engineering properties of the wastes placed in the fill and of the soils, synthetic materials, or both used to isolate the waste from the environment. This type of analysis should be performed by a qualified and experienced professional, and is usually reserved for a geotechnical engineer.

The shear strength of solid waste is an important mechanical property used in the analysis and design of waste slopes [87,88]. The amount of moisture in the waste can affect the shear strength and slope stability of the waste.

G3. BOTTOM liner

A bottom liner (or, simply, liner) is an engineered system to contain and control the pollution of the land and water environments surrounding the land disposal operation. The design of a bottom liner, in the case of economically developing countries, will vary depending on a number of factors, including: the potential of the landfill polluting the land and water environments, the local hydrogeology and meteorology, and the availability of suitable materials and monetary resources. Liners are described in detail later in this chapter.

G4. DAILY, intermediate, and final covers

The technology of modern sanitary landfilling includes cover systems over the waste to control nuisances, to protect the environment, and to protect the health and safety of workers and of the public. Depending on the location within the fill and the phase of the construction and operation, the cover systems employed are daily, intermediate, and final. The daily and intermediate covers are placed more or less continuously during the active phase of the filling operation. The final cover usually is periodically placed during the active phase of the landfill or at the completion of the fill. Of the three, the final cover is the most complex system. In the context of economically developing countries, the design and materials of construction of each of the three types of cover systems are subject to the short- and long-term risks posed by the operation of the fill, to the availability of suitable materials, and to financial resources. The three types of landfill cover systems are described below.

G4.1. Daily cover and intermediate cover

Daily cover controls vectors, litter, odours, fire, and moisture. Any soil material that is workable and has stability (clays, gravels, etc.) may be used.

Intermediate covers control gas migration and provide a road base. Soils used for intermediate cover must have strength and the required degree of impermeability. Typically, a thickness of 15 to 20 cm of compacted soil is recommended.

The application of cover over the waste on a daily basis controls the generation of nuisances and hazards to the operators and to the public. However, in some situations, the application of cover on a daily frequency may not be warranted as a consequence of an assessment of the risk of hazard and nuisances versus the availability of material and financial resources. These situations would be most likely to exist in arid locations in which the average rainfall does not exceed about 10 cm/yr and the evaporation rate is about the same on an annual basis. Under these conditions and assuming that the groundwater is not in any danger of contamination and that the operators or public are not exposed to some other unacceptable risk, it may justified to cover the waste on a frequency that is less than daily. An analysis of the situation and local conditions is required in order to determine the frequency of covering waste.

Lack of availability of native soil for cover is not necessarily an adequate reason for infrequent covering of the wastes. Alternatives to native soil exist in some cases. For instance, a large number of municipalities in developing countries have a large market that generates considerable quantities of organic matter. This material usually is landfilled. Instead, the material can be composted together with residues from landscaping and used as cover material. Generally, one can find a number of alternative cover materials that can replace soil after adequate analysis of local conditions and after processing of the materials, if necessary.

G4.2. Final Cover

The final cover is the layer that is placed on the completed surface of the fill. The functions of the final cover are several. It controls infiltration of water (and, hence, indirectly controls leachate production), controls landfill gas migration, serves as a growth medium for vegetation, provides a support for post-closure activities, and is a barrier between the external environment and the waste [8].

An important consideration in the design of a final cover is the degree of resistance that the cover offers to percolation and infiltration of moisture and to the upward migration of gases generated in the buried waste. This resistance may or may not be desirable. Thus, some cover designs call for the free percolation of rainwater through the cover; whereas, others call for resistance to such percolation.

In the cases where high runoff and minimal cover percolation are the main criteria in cover design, soil hydraulic conductivity is one of the more important design parameters in controlling percolation [8]. Percolation decreases as the number and thickness of layers in the cover increase.

The most resistant to percolation of the two-layer soil covers consists of a topsoil surface layer over a hydraulic barrier layer composed of a properly designed mixture of clay and loose-textured soil.

Other considerations regarding the design of the final cover involve the intended use of the completed fill. A relatively loosely textured soil cover provides a good growth medium for vegetation, even if the vegetation is intended solely for the purpose of encouraging water loss through evapotranspiration. However, a loosely textured soil cover does not provide the maximum possible load-bearing capacity. If eventual gas recovery is a goal, the upward flow of gas must be prevented. If structures are to be built on the completed fill, the maximum withdrawal of gas should be promoted. Finally, regarding all considerations pertaining to penetration, it should be kept in mind that a tightly compacted clay cover resists penetration, whereas a sandy or gravely cover material offers little if any resistance.

The simplest design of a final cover system for a sanitary landfill consists of two layers: 1) the surface layer, and 2) the hydraulic barrier. The hydraulic barrier essentially is the first layer of the cover specifically designed to prevent the passage of liquids into the waste.

If a cover is to be designed and implemented in a developing country, it is advisable to use a thickness of about 60 cm for the surface layer and a thickness of 30 cm for the underlying hydraulic barrier. This design would be acceptable in areas with high evaporation and low rainfall (i.e., a climate with high temperatures, low humidity, and low precipitation). The design of the cover is depicted in Figure XIV-10.

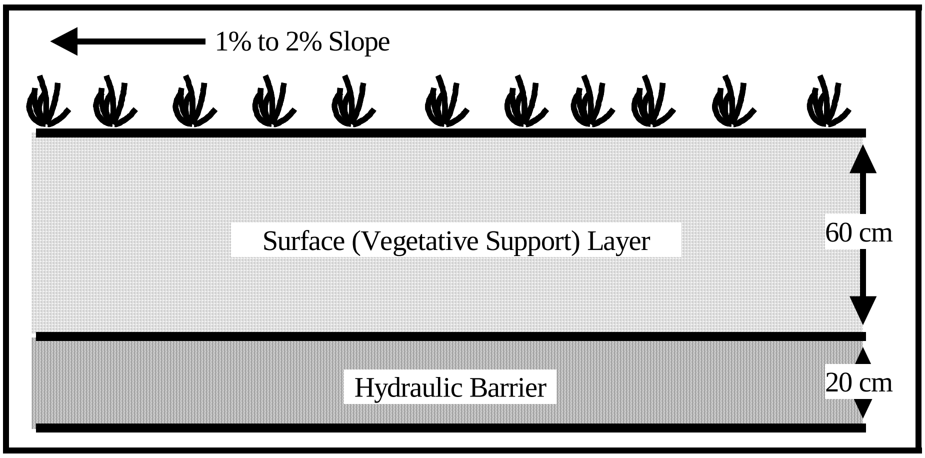


Figure XIV-10. Basic design of final cover system

In humid climates and in those situations that require a high level of control, the inclusion of other types of layers may be necessary.

In order to maintain the flow of water into the solid wastes to a minimum, the cover must be designed such that the major portion of precipitation becomes runoff. This objective can be accomplished by building a cover with a slope between 1% and 5%. This inclination promotes flow off the cover and at the same time limits erosion to an acceptable level. Erosion also is reduced by establishing vegetation. Vegetation also has an additional benefit because it promotes evapotranspiration. Thus, slope and vegetation play important roles in the performance of the cover.

In the event that the layer of topsoil does not have a sufficiently low permeability to prevent percolation, then the waste will be subject to infiltration and, thus, the potential generation of leachate. Infiltration can be reduced by the incorporation of a lateral drainage layer above the hydraulic barrier layer. The incorporation of the drainage layer into the design brings about a higher degree of control of leachate formation and also increases the complexity of the cover system and the cost. The increase in the complexity of the system and in the cost may not be acceptable in economically developing countries. The reason is that if the drainage layer is to function properly, it should be protected from above by a filter zone. The filter zone consists of a layer of carefully selected and sized cohesionless soil. The filter zone, as its name implies, serves the purpose of preventing the downward migration of small soil particles from the vegetative layer into the drainage layer. These particles would eventually clog the drainage layer.

Finally, if brush and tree growth is promoted and burrowing animals are present, it would be necessary to include a barrier to keep the roots and animals from damaging the cover. This additional layer is called a biotic barrier. This barrier generally is located between the filter and drainage layers.

The main aspects of the design of a cover are its individual layers. The schematic in Figure XIV-11 shows the state-of-the-art in the design and construction of landfill covers as employed in the United States. As shown in the figure, eight different layers compose the complex cover system of a modern sanitary landfill.

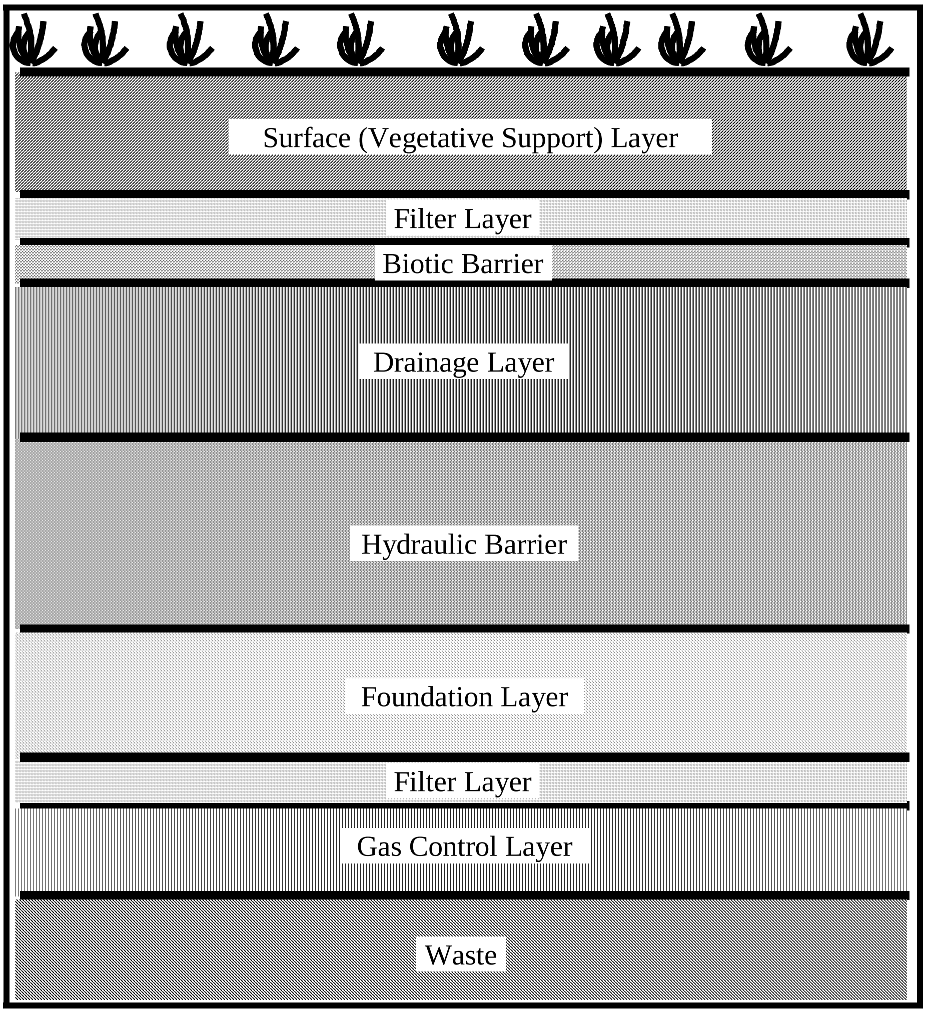


Figure XIV-11. Components of a complex final cover system of a modern sanitary landfill

Each of the eight layers is described in the following subsections.

G4.2.1. Vegetative (or surface) layer

This layer is necessary to protect the cover from erosion due to wind and water flow. The surface or vegetative layer should consist of nutritive and dense topsoil in order to support plant growth. The soil can be mixed with composted yard debris, biosolids, or animal manures.

G4.2.2. Filter layers

Any time soils having fine particles are placed over soils with coarse particles, there is potential for the movement of the fine soils into the voids of the layer of coarse grains. This phenomenon is known as piping and results in the plugging of the coarse layer. Filter layers are used in the design of landfill covers both to remove fine particles from infiltration and to allow upward flow of landfill gases. Soil or non-soil particulate filters can be used. In the event that they are not available, geotextiles may be used.

A filter layer also is usually placed below the foundation layer to prevent clogging of the gas control layer.

G4.2.3. Biotic barrier

As previously indicated, the hydraulic barrier plays a very important role in the performance of a cover. As such, the integrity of the hydraulic barrier must be maintained. Plants and animals can perforate the hydraulic barrier and, thus, compromise its integrity. One method of controlling this potential problem is through frequent mowing and pruning of the plants and through the use of rodenticides. Another method of control is through the installation of a biotic barrier. A biotic barrier consists of a layer of construction debris, crushed rock, or similar material of such size to prevent the movement of roots and animals.

G4.2.4. Drainage layer

If a final cover is incorporated into the design of a landfill, it should incorporate a drainage layer. The few exceptions would be in very arid areas where precipitation is very low. The main purpose of this layer is to intercept the downward flow of infiltration and to remove it before it can penetrate the hydraulic barrier.

A schematic of a drainage layer is shown in Figure XIV-12. As is depicted in the figure, the layer should slope in the direction of collection points on the perimeter of the landfill. The drainage layer should be made up of porous material.

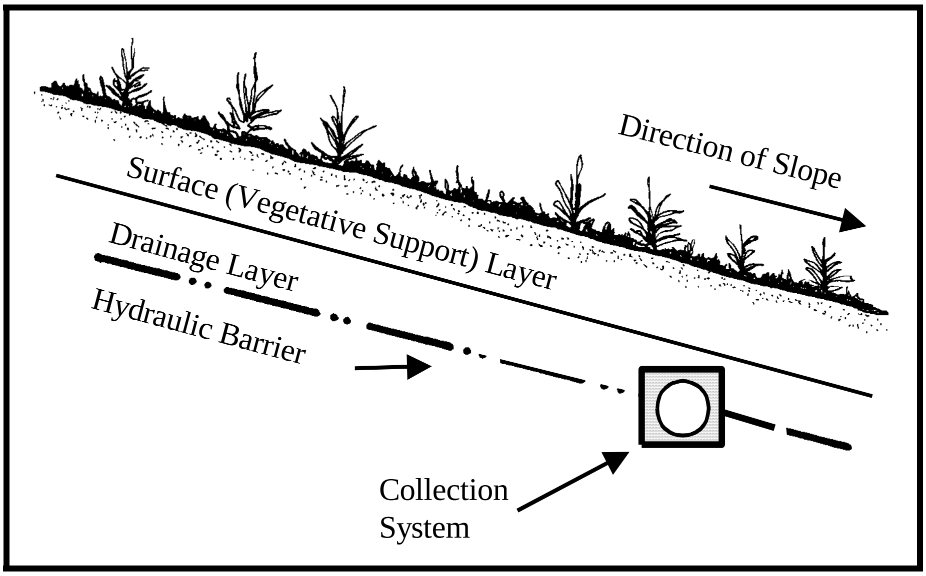


Figure XIV-12. Schematic of a drainage layer

G4.2.5. Hydraulic barrier

The hydraulic layer is one the most important components of a final cover. The main function of the hydraulic barrier is to prevent infiltration of moisture into the solid waste and, thus, prevent the formation of leachate.

In industrialised countries, hydraulic barriers are made of fine-grained soil that is carefully compacted. The soil can be mixed with other materials such as bentonite clay and fly ash in order to reach the desired permeability. Proper performance of the final cover depends upon the maintenance of the integrity of the hydraulic barrier. In order to perform effectively over time, the thickness and hydraulic permeability of the soil barrier layer should be at least 30 cm and less than 1×10^{-6} cm/sec, respectively. The ideal design is a thickness of 60 cm and a permeability of less than 1×10^{-7} cm/sec.

The integrity of the hydraulic barrier can be affected through three mechanisms: mechanical, chemical, and environmental. Mechanical impacts deal primarily with damage due to construction, such as excessive overburden, high compaction, and punctures. Chemical effects are the least troublesome and relate to vapours and gases. Environmental impacts involve drying, wetting, and root penetration.

Synthetic membranes can be used instead of soil as hydraulic barriers. Synthetic membranes can be very expensive for these applications, particularly in the small municipalities of economically developing countries. If synthetic membranes are used, they should be protected from mechanical damage (both during construction and maintenance) by installing adequate underlayment and a protective layer (such as sand) on top.

G4.2.6. Foundation layer

As its name implies, the foundation layer serves as a buffer between the final cover and the wastes it is designed to support. The foundation layer is made up of compacted soil placed on top of the uppermost waste lift.

One of the main concerns in the design of a final cover is settlement due to decomposition of the wastes. Consequently, one of the more effective means of protecting the foundation layer, and therefore the final cover, is by ensuring that the wastes are thoroughly compacted.

G4.2.7. Gas control layer

Landfill gas is a product of decomposition of organic matter in the landfill. The gas is primarily composed of methane and carbon dioxide. The quantity and composition of the gas depend upon a number of variables, including: nature of wastes, climate, and moisture content.

Gas control mechanisms typically utilise a porous layer placed as close to the waste as possible. The layer may be part of a static or dynamic gas collection system.

G5. CUSTOMISED methods of construction and use after completion

The design and construction of a sanitary landfill may be customised so as to accommodate both waste disposal and use of the facility after the completion of the active phase of the fill. Some examples of feasible uses are topographical contouring, reclamation of aquatic environment, strip mine reclamation, urban redevelopment, and gas recovery. The use of a landfill after its active life entails special considerations.

Two particular types of customised landfill construction and uses are described below: topographical contouring and reclamation of aquatic environment. Other potential uses and their implications in terms of design and maintenance of the fill are discussed later in this chapter.

G5.1. Topographical contouring

Topographical contouring is the construction of a fill in the form of a hill. This approach allows more efficient use of the land by increasing the capacity of the landfill in a given area. The completed fill consists of a series of circular lifts tapered to approach the contour of a hill. In this case, the area method would be used for building the lifts. The maximum slope of the hill is determined by the angle of repose of the soil cover, the climbing capacity of the equipment, and the angle of slip and tip (roll over) of the equipment when operating at normal loading. The design specifications should provide a comfortable safety factor with regard to these items. The maximum grade of the slope must be one at which several requirements (e.g., spreading, compaction, covering) for a satisfactory fill can be met without endangering the safety of the workers, and at which the eventual landscaping of the hill can be done. Other factors that must be considered and addressed include soil erosion caused by precipitation and slope stability.

G5.2. Reclamation of aquatic environment

In some cases, the landfilling of solid waste may be justified for the reclamation of marshes and other land masses containing pockets of water with very low quality. In these situations, the water is removed or allowed to evaporate and the appropriate evaluations are carried out (geological, hydrological, and others). Careful consideration must be given to the ecological conditions of the site. For the improvement and maintenance of the public health and safety, solid waste should not be disposed in or near existing or potential sources of water used by humans for drinking, cleaning, or recreation, or in ecologically sensitive areas. Prior to the implementation of a coastal reclamation project, all potential environmental consequences must be carefully identified and analysed.

G6. CO-DISPOSAL of special wastes

Co-disposal involves the mixing of one type of waste with another and the subsequent disposal of the mixture. Although the co-disposal described in this section can be applied to most types of non-industrial sludges, the discussion is directed primarily to sludges (biosolids) associated with the storage, treatment, and disposal of human body-wastes (primarily, faecal wastes). Examples of the latter biosolids are those produced by a conventional wastewater treatment facility, septic tank pumpings, sludge from the storage pits of unsewered public toilets, and nightsoil in general.

Despite the many hazards to public health and nuisances attributed to the practice, untreated nightsoil frequently is co-disposed with municipal solid wastes in developing countries. These hazards and nuisances are amplified by the prevalence of the open dump method of disposal. Although perhaps not as pronounced, the same hazards attend the open dump co-disposal of primary (i.e., raw) sewage biosolids from a sewage treatment facility. The hazards can be substantially reduced by converting to sanitary landfilling.

In an operation involving co-disposal by sanitary landfilling, an approach is to deposit the biosolids (20% to 30% solids) on top of the solid waste at the working face of the landfill. The biosolids and solid waste are thoroughly mixed. The mixture is then spread, compacted, and covered in the manner usual to the sanitary landfilling of solid waste. Liquid in the biosolids is absorbed by the solid wastes. Because the absorption capacity of municipal solid waste in developing countries generally is relatively low, the maximum weight of the water in the biosolids must be low in order for the solid waste to retain the water contained in the biosolids so that it does not contribute unduly to leachate generation. Scavengers should not be permitted to come in contact with biosolids or solid wastes that have received biosolids.

G7. HAZARDOUS wastes (secure landfill)

G7.1. Introduction

Although the management of hazardous wastes is not the main concern of this book, the technology for disposing of these wastes is briefly covered for completeness and as a reminder of the importance of their management. Furthermore, in most developing countries, a large fraction of the hazardous wastes generated are collected and disposed with the municipal solid wastes.

The land disposal of hazardous waste can pose a substantial risk and undertaking in a developing country since definitions, standards, and safeguards usually are not developed or fully operative.

G7.2. Definition and specifications

A secure landfill is a complex, engineered earthen excavation specially designed to contain hazardous wastes such that they cannot escape into the environment. Therefore, a genuinely secure landfill has the following features:

- Waste disposed in a secured landfill is completely enclosed by one or more layers or liners of impervious materials.
- The distance between the bottom of the liner and the groundwater is sufficient to prevent contact between the two.
- Leachate and all other liquids are not allowed to accumulate inside or outside the containment layers.
- Groundwater quality is monitored such that leakage from the fill can be detected and corrected.

- The fill is located such that it is isolated from surface and subsurface water supplies; is free from the effects of flooding, earthquake, or other disruptions; and its site is not needed for other uses after the facility is closed [29].

G7.3. Design

As with all sanitary landfills, the design of a secure landfill largely depends upon the hydrogeological characteristics of the site. Thus, if the distance to the water table is substantial and the soils are impermeable, compaction of the soils at the site combined with the placement of a single liner, either of natural or of synthetic material, would be sufficient. In such a case, soil or bentonite could serve as a natural liner material and high-density polyethylene or chlorinated polyethylene could serve as a synthetic liner material. If conditions are not ideal, but do meet minimum standards of acceptability, the soil presently at the landfill site could be excavated and replaced with a sand/gravel layer, followed by a compacted clay layer, a synthetic liner, and a final layer of compacted clay. In all cases, provision should be made for preventing the various types of wastes from mixing together and thereby triggering a dangerous chemical reaction (e.g., highly caustic waste with a strong acid waste). Prevention of mixing is effected by separating different areas of the facility from one another by forming subcells using earthen dikes.

Arrangements should be made for collecting and withdrawing leachate as it accumulates in the basin. This is done through a network of piping installed in the fill. Groundwater quality should be monitored by means of monitoring wells placed along the perimeter of the fill. Monitoring of groundwater should take place before the beginning of the deposition of wastes and be continued thereafter until chances of pollution become non-existent.

The design, operation, and monitoring of a secure fill is a complex process that requires the participation of skilled professionals. The various elements of a secure fill are diagrammatically indicated in Figure XIV-13.

G7.4. Closure of the fill

The closure operation is designed such that total and complete containment of the facility is assured, and that the completed fill does not pose a threat to the public safety and the environment. This objective is attained by adhering to the following procedure:

- Upon completion of the landfill, cover the upper surface of the completed fill with impermeable soils.

- Cover this layer with a synthetic liner (if available) to effectively seal this layer and underlying wastes from rainfall.

- Cover the synthetic liner with topsoil and seed the topsoil to produce vegetation to complete the closure operation. Leachate and gas collection pipes should protrude through the final cover.

Finally, excavation of the completed fill should not be attempted since most buried hazardous wastes continue to be dangerous long after their burial. Excavation of completed, secured landfills can be a dangerous undertaking.

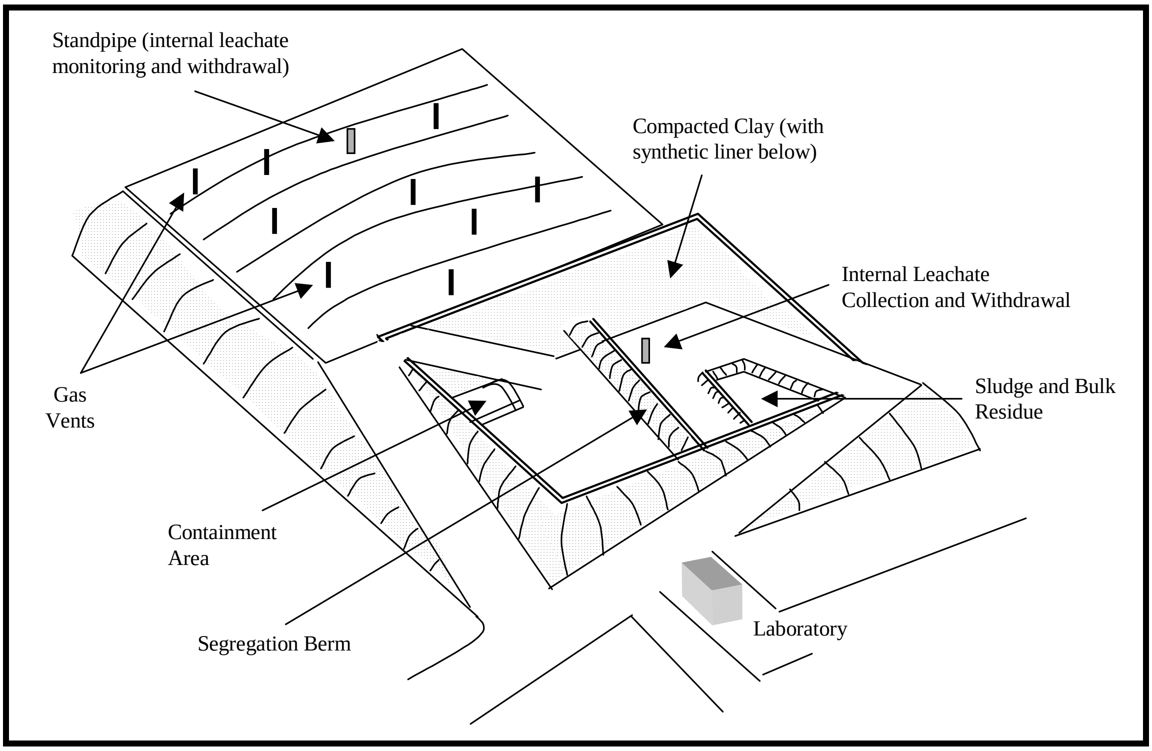


Figure XIV-13. Typical layout of a secure landfill

H. Development of the landfill

This section describes the steps involved in preparing a site for an orderly and sanitary operation.

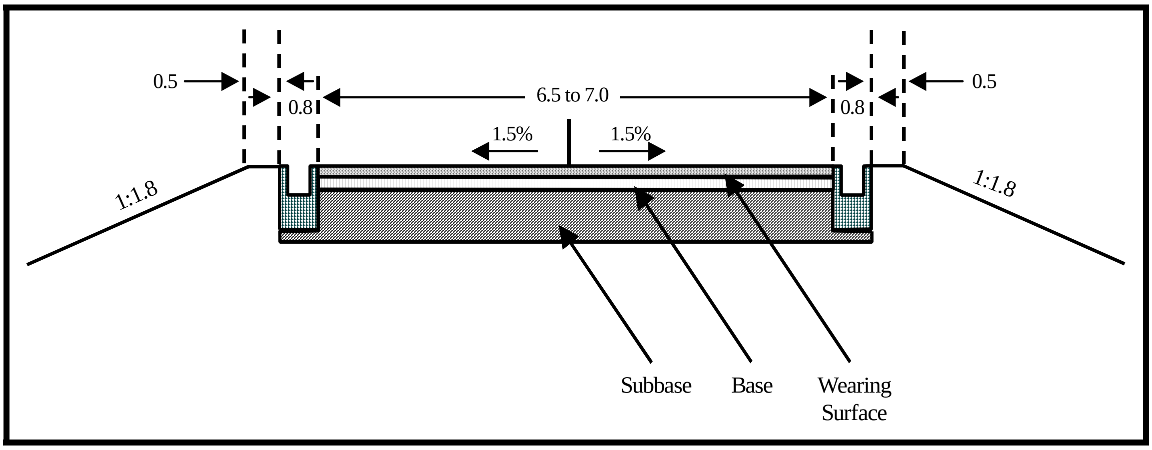
H1. TERRAIN upgrading

One of the first steps in the development of a sanitary landfill involves the removal of all objects that may interfere with the operation and movement of vehicles and equipment. Consequently, trees, shrubbery, and other interfering vegetation should either be cleared from the site, or restricted to its periphery.

Secondly, the site must be graded so as to eliminate interfering surface irregularities. The surface of the site should be contoured such that a controlled runoff is promoted and ponding is prevented. Appropriate measures should be employed for minimising problems associated with erosion, the generation of dust, and sedimentation. To avoid danger of erosion and scarring of the land and to allow close supervision, large sites should be cleared in phases.

H2. ROADS

All-weather (permanent) access roads from the public road system to the site should be provided. With large sites, these access roads would be extended from the site's entrance to the vicinity of the working area. The roads should be designed to support the anticipated volume of pedestrian and vehicular traffic. Before the access roads are designed, it also is important to determine the size of vehicles and their probable range of speed, as well as the minimum service standards to be maintained. Adequate drainage should be provided to prevent the roads from flooding during wet seasons. Ideally, the roadway should consist of two lanes (minimum total width, 7 m) for two-way traffic. Grades should not exceed motorised equipment limitations: uphill grades, less than 7%; downhill grades, less than 10% [29]. Although the initial cost of onsite permanent roads may be higher than that of temporary roads, the difference in cost is more than compensated by savings in equipment repair, maintenance, and time. Finally, the roads should be built to meet national standards. A cross-section of a typical access road is presented in Figure XIV-14.



[a] Dimensions are in meters.

Figure XIV-14. Typical cross-section of access road[a]

Because the location of the working face is constantly changing, roads for the delivery of wastes from the permanent road system to the working face usually are temporary in terms of nature and construction. Temporary roads may be constructed by compacting the native soil and by digging drainage ditches. The roads may be topped with a layer of tractive material, such as gravel, crushed stone, cinders, broken concrete, mortar, or bricks. The use of lime, cement, or asphalt binders may increase the serviceability of the temporary roads. Road width is a function of road alignment and traffic volume. However, the width should be at least 3.5 m for a one-lane road and 6 m for a two-lane road.

If the expected truck traffic is only 25 to 50 round trips/day, a roadway composed of a graded and compacted soil usually would suffice. Traffic consisting of more than 50 trips/day probably would justify the use of calcium chloride as a dust inhibitor, or of binder materials such as soil cement or asphalt. Traffic consisting of more than 100 to 150 trips/day would necessitate a base plus a binder. The types of vehicles using a landfill will range from modern collection trucks to primitive forms of transportation, such as some of those described in the chapter on storage and collection. The types of vehicles using a landfill must be considered when designing the roadways in the fill.

H3. MEASUREMENT of weight (scales)

The importance of having an accurate knowledge of the gravimetric and volumetric amounts of wastes delivered to the disposal site has been discussed in previous chapters. Therefore, to the extent feasible, all incoming wastes should be weighed. In some situations, it may be necessary to install more than one scale in order to avoid long queues and to record the weight of the empty vehicles as they exit the site.

Types of scales range from highly automated electronic scales to simple, portable beam versions. The platform, or scale-deck, may be constructed of wood, steel, or concrete, such that the scale is horizontal and on a firm foundation. The scale should be able to weigh the largest vehicle that will come to the landfill on a routine basis. A capacity of 30 to 60 Mg probably would be adequate. Ideally, the platform should be long enough to weigh all axles simultaneously, although separate axle-loading scales (portable versions) would suffice for small operations. A photograph of a truck scale is presented in Figure XIV-15.

Courtesy: CalRecovery, Inc.

Figure XIV-15. Collection vehicle being weighed on a truck scale

The accuracy of the scale should be checked periodically using known weights.

H4. UTILITIES

Ideally, electrical, water, and sanitation services should be provided. However, the likelihood of all three being available at a disposal site in a developing country is unlikely. Electricity can be used for illumination and power. These two uses are almost essential if equipment maintenance and repair are to be done at the site. Electricity can be generated at the site by means of a portable generator. Water should be available for drinking, fire fighting, dust control, and employee sanitation. In the absence of access to a sewer, ventilated latrines should be built and maintained.

H5. STRUCTURES

If feasible, and particularly at large disposal operations, a structure or set of structures should be erected to provide office space; to house employee facilities; to provide a sheltered area for equipment storage, maintenance, and repair; and to serve as a scale house. The office space is needed for recordkeeping and the required clerical activities. Employee morale, well being, and efficiency are substantially benefited by providing a structure that includes: first aid facilities, provisions for workers' washing and changing, toilet facilities, and a canteen. The equipment structure serves as garage and repair shop. Buildings that will be used for less than ten years should be of temporary construction and preferably be movable. The design and construction of all buildings should take into consideration landfill gas migration and differential settlement of the fill. If these facilities are not provided at any but the smallest disposal sites, operation of the landfill will be impeded or compromised.

H6. FENCING

Access to the landfill site should be controlled preferably by building a fence around the entire perimeter of the site or, at the very least, around the locations of easy access to equipment and wastes by unauthorised individuals. A fence also serves to restrict access to the waste by animals, screens the landfill, and delineates property lines. The type and height of the fencing are determined by the available resources and conditions prevailing at the site. Fencing of about 1.5 m in height and with a minimum of 5 cm openings usually is adequate.

Litter fences should be erected in the immediate vicinity of the working face to control blowing paper and other litter. A low (about 1 m) fence usually suffices at a trench operation; whereas, a 2 to 3 m height may be necessary at a windy, area-type operation. Litter fences should be portable. A diagram of a litter screen is presented in Figure XIV-16.

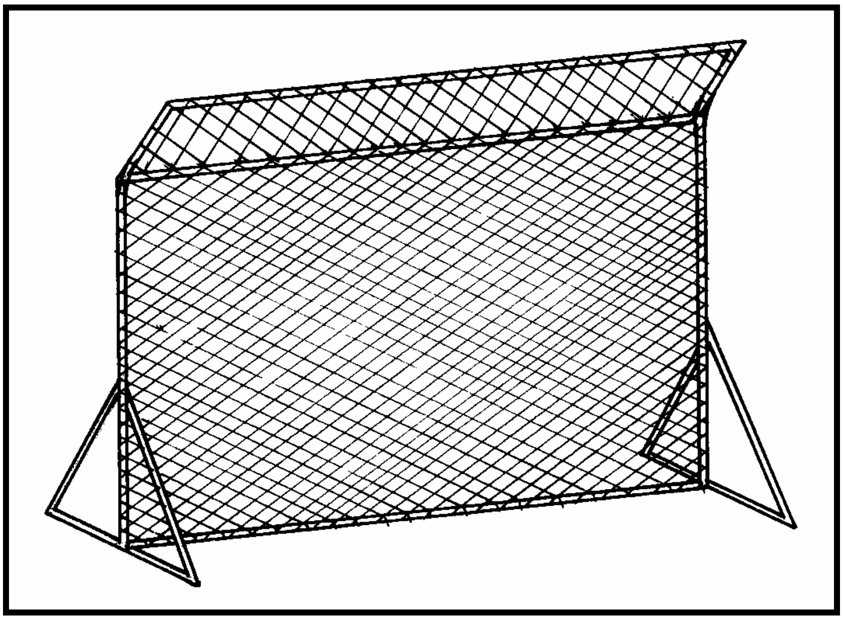


Figure XIV-16. Portable litter fence (2 m high, 3 m wide)

I. Operation

I1. INTRODUCTION

This section presents an approach for the efficient operation of a solid waste landfill. A detailed outline of all daily activities is the basis of an effective operating plan. The plan must be sufficiently flexible to encourage managerial ingenuity in reaching the objectives, and sufficiently rigid to support proper operations. An efficient operating plan implies equipment that is compatible with the characteristics of the solid waste, the site conditions, and the method of landfilling

In this section, site operation is divided into two parts: 1) operational procedures that do not depend upon the method employed for landfilling, and 2) operational procedures that are specific to the method of landfilling.

I2. GENERAL operating procedures

Operation of a sanitary landfill requires a series of activities, some of which are normally conducted continuously while others are conducted at a fixed frequency. Some of the more important operational procedures that must be considered for all methods of landfilling include:

- preparation and maintenance of the site,
- environmental control,

- hours of operation, and
- procedures during inclement climate.

A discussion of each of these key items is presented in the following sections.

I2.1. Site Preparation and maintenance

I2.1.1. Site preparation

Site preparation is an important aspect of the general operating procedures of a sanitary landfill. As a particular cell is completed, new areas must be cleared, excavated, and lined (if necessary). Similarly, as the working areas are filled, a final cover should be applied on them as soon as possible.

The sites must be prepared and constructed according to design specifications. Site preparation and construction include:

- clearing and grubbing,
- installation of leachate control systems,
- erection of structures,
- installation of utilities,
- constructions of roadways, and
- soil stockpiling.

I2.1.2. Road maintenance

Maintenance of access roads at landfill sites is one of those activities that should be conducted on a continuous basis. If performed well, road maintenance often is an expensive operation. Regardless of the type of surface (soil, gravel, or pavement), the roads must be inspected and repaired frequently. Typical repairs include cleaning, adding or grading soil and gravel, filling holes, and cleaning drainage ditches. Since road maintenance is a costly operation, typically it is neglected. Unfortunately, lack of proper road maintenance leads to equipment damage, unnecessary delays in operations, and safety problems. It may be advisable to leave a few sections of well marked rough areas on some roads in order to control excessive speed by vehicles using the site.

I2.1.3. General maintenance

All waste treatment and disposal sites require continuous care. The site manager is the person responsible for the preparation of a detailed maintenance schedule. Specific dates should be scheduled for the performance of the following tasks:

- collection and disposal of litter;
- relocation of portable fences for the management of litter;
- maintenance of gates, fences, and structures;
- maintenance of drainage system and final cover; and
- preparation and upkeep of final site maps.

As areas of the site are completed, a series of maps indicating the status of filling phases should be updated. The maps should identify areas used for special wastes, the fill depth of the various areas, the type of waste disposed, as well as other site-specific features.

I2.2. Environmental control

In most situations, regulations are established that require the inclusion of environmental controls in the design and operation of a landfill in order to protect the public health and the environment from potential negative impacts of landfills. The most commonly used types of environmental controls include impermeable barriers (liners), leachate collection and treatment systems, landfill gas management systems, and cover systems. The proper design and construction of these control systems are discussed throughout this chapter. Environmental controls are necessary to protect the environment during landfill operation and during the closure and post-closure periods. These practices are described in the following sections.

I2.2.1. Siltation and erosion

Runoff having relatively high concentrations of silt usually is brought about by improper grading. Grades with a slope of 2% to 5% should be maintained, where feasible, to promote surface drainage but at the same time to control flow velocities to acceptable levels. Denuded areas should be kept to a minimum during site operation. Ongoing construction and maintenance of sediment control devices (e.g., diversion ditches, rip-rap, sediment basins) are critical for an environmentally sound operation. During final closure and the post-closure period, proper final grading, seeding, and maintenance of a final cover system help prevent long-term problems as a consequence of erosion and siltation.

I2.2.2. Mud

Heavy rains and snow melt can result in the production of mud. In order to reduce the undesirable effects that mud can impose on daily operations, access roads should be elevated somewhat above the surrounding ground level, and paved or gravelled. Another alternative for road base where vehicular traffic is frequent is to mix soils of large particle size such as sand and gravel with clay soils. Mud can be tracked onto public roadways by landfill equipment or collection vehicles and can result in poor public relations for land disposal facilities [25]. Ideally, if the site is prone to muddy conditions, an area for washing the vehicles should be installed near the gate to the facility for the purpose of vehicular cleaning. Specific areas of the site should be identified for use during poor weather conditions and when conditions in other areas of the facility are muddy and would make operation difficult. Wet weather operation areas should be located as close to the main gate as possible in order to reduce onsite travel.

I2.2.3. Dust

Dust is generated at a landfill site by two main sources: 1) collection vehicles and heavy equipment moving over dry dirt roads, and 2) the wind. Dust can also be generated during the discharge, placement, and compaction of unusually dry materials or during the excavation and movement of dry soils. To reduce the amount of dust generation, access roads should be gravelled or paved. As an alternative, water or other environmentally acceptable dust control chemicals can be applied to dirt roads on a continuous basis. The practice in some developing countries of applying waste oils to roads should not be used because of the potential of pollution of land and water resources. Excavating or moving soils when they are damp also will limit dust production. Similarly, when a load of dry waste materials is brought to the landfill, it should be slightly moistened prior to disposal. Another means of reducing the total amount of dust generated from a particular facility is to revegetate completed areas as soon as possible.

Landfills should be equipped with a water truck or trailer to moisten dirt roads and working areas for dust control.

I2.2.4. Vectors and pests

Flies, mosquitoes, rodents, birds, dogs, and other animals are an occurrence at landfill sites. Vectors can be controlled by frequently placing an adequate quantity of compacted soil over the wastes or by chemical means, and by maintaining the smallest possible working face. It has been demonstrated that a daily cover consisting of 15 cm of compacted soil having a low clay content will prevent the emergence of flies. However, even under the best program of prevention and site conditions, a landfill should have a regular inspection and fly control program. Mosquito control is best accomplished by preventing the accumulation of stagnant water anywhere on the site (e.g., in old tires and depressions). The accumulation of stagnant water on the surface can be prevented by properly grading the surface, by filling depressions, and by placing cover soil over waste materials.

Occasionally, rats and mice may be delivered to the site with the solid waste. If harbourage occurs in areas adjacent to or in some neglected portion of the site, extermination by the local health department will be necessary. Employees at the landfill should be trained to recognise burrows and other signs of the presence of rats and mice so that appropriate management procedures can be put into force.

Although they may not be classified as “vectors” in the strict sense of the term, birds are discussed in this section because certain types become pests when considered in the context of a landfill operation. Birds generally are attracted to a landfill in search of food. This is particularly the case in landfills located in coastal areas, although most landfills will attract one type of bird or another. Birds can pose a serious hazard to aircraft and create a nuisance to landfill personnel and neighbours. In the United States, criteria for the classification of waste disposal facilities and practices indicate that solid waste facilities should not be sited within 3 km of an airport serving turbojets [26]. On rare occasion, certain species (for example, seagulls) can serve as vectors for certain diseases by way of their droppings or by serving as hosts to insectivorous vectors. As is true with problems arising from other pests, the bird problem is best met by rapidly and completely covering all wastes. Noise production, distress calls, or similar measures can provide some temporary control, but usually are not found to be consistently successful.

Access to wastes by animals such as pigs, cattle, sheep, and others should be strictly prohibited because of their ability to transmit pathogens directly or indirectly to humans.

I2.2.5. Odours

Several potential sources of unpleasant odours exist at landfill facilities. Odours may be generated in the following situations:

- at the time the waste is delivered,
- from decomposing waste in place at the landfill, and
- from storage ponds and liquid treatment systems.

Odours generated at the time the waste is delivered can usually be mitigated by rapidly covering the wastes and ensuring that the cover is maintained intact.

Occasionally, loads of particularly malodorous materials (e.g., market or fish processing wastes) may be delivered to the landfill. If at all possible, deliveries of these materials should be scheduled such that sufficient workers and equipment are available to immediately cover the waste. If not possible, malodorous loads can be mixed or covered with other wastes in order to control the problem. In some cases, the application of lime and/or chemical masking agents to the wastes can achieve some degree of door control.

I2.2.6. Noise

The primary sources of noise at landfills are operating equipment and collection vehicles. The noise generally is very similar to that generated by any heavy construction activity, and is limited to the site and to the streets used to transport the solid waste to the site. In order to reduce the total number of individuals exposed to the noise, every effort should be made to route traffic through the least populated areas. In addition, the site should be isolated or surrounded by a buffer zone such that the noise will not disturb neighbours. The installation of noise barriers such as berms, walls, and trees are effective measures of control.

I2.2.7. Aesthetics

In order to maintain environmental impacts to a minimum and to make the landfill acceptable, the site should be designed to be as compatible with its surroundings as possible. During site preparation, it is important to leave as many trees as possible to form a visual barrier. Berms can also be used to form visual barriers. The use of architectural effects at the entrance, confining disposal to designated areas, and the use of attractive landscaping will assist in the development of an aesthetic facility. Additionally, every attempt should be made to minimise the size of the working area.

I2.2.8. Litter

One of the most frequent complaints from residents living near landfills concerns blowing litter, particularly light materials such as papers and plastics. Blowing litter can be substantially reduced by:

- discharging the waste at the toe of the working face,
- application of water or damp waste to loads containing a high concentration of paper and/or plastics, and
- installation of portable or stationary fencing around the working face.

In addition, if soil cover or another material is available, frequent and thorough covering of the face and completed portions of the cell can play an important role in the control of litter.

Generally, despite the operators' best efforts and control measures, the accumulation of some litter is inevitable at a landfill site. The installation of a fence around the site or downwind from the site will help to contain litter and keep it from reaching adjacent property. Daily cleanups, particularly at the end of the working day, can limit the quantity of litter that can eventually reach other property.

I2.2.9. Fires

Potential sources of fires at landfills include receipt of wastes containing hot embers, sparks from vehicles, equipment fire, and vandalism. A good security program, combined with alert vehicle spotters, can control most of the problem. Hot and highly flammable wastes should be directed to special areas in the landfill and moistened or smothered with soil prior to disposal. All landfill vehicles should be equipped with fire extinguishers to limit damage in the event of an equipment fire.

If a water line is not available, a water truck or trailer equipped with a gas-powered pump should be always be on-hand at all but the smallest landfills. There are several techniques available for managing landfill fires. Fires near the surface of the fill can be excavated and extinguished with soil and/or water. Deep fires can sometimes be extinguished by placing damp soil on the surface of the fill, by injecting water into the burning section of the fill, or by excavating and extinguishing the waste. Deep landfill fires are very difficult to extinguish completely.

If landfill gas collection systems are present in a landfill where waste is burning, their continued operation must be given due consideration. Gas extraction wells can draw air into the fill and thus be a source of additional oxidiser (oxygen). Additionally, the wells can collect the byproducts of the waste combustion products, which can lead to degradation or destruction of the wells, piping, and control systems [90].

Open burning of combustible materials should be strictly prohibited at all disposal sites. The common practice of open burning for volume reduction or for salvaging (i.e., removal of insulation from aluminium and copper wire) should not be allowed at any type of waste disposal facility.

I2.3. Operating hours

The operating hours at a landfill typically are set by the collection schedules. However, in some cases, collection practices can be modified to accommodate site operations. Generally, landfill sites in the United States are open from about 6:00 am to mid to late afternoon. The hours of operation of both the collection system and of the landfill should take into consideration local traffic conditions.

Operating hours may be modified based upon the quantity of waste produced during a certain time of the year. In the event that the site is not open 24 hr/day, the gates should be closed sufficiently early to allow for covering of the waste and general cleanup. Containers may be placed outside the gate to allow for the disposal of small quantities of wastes after operating hours.

Personnel should arrive at the facility sufficiently early to prepare the equipment and the site before the arrival of collection vehicles. Some of the tasks that are carried out prior to the arrival of collection vehicles include: snow plowing (where appropriate), relocation of fencing for litter, maintenance of equipment, fuelling, preparation of unloading areas, and cleaning of roads.

I2.4. Inclement climate

Climatic conditions can significantly affect the operation of a landfill. Long periods of excessive rainfall, freezing temperatures, or extreme heat can disrupt routine operation of a landfill.

The relative amount of rainfall during site preparation has a direct impact on the moisture content of the soil, as well as on groundwater saturation levels. Both of these parameters are important in the control of soil strength and permeability during construction of a clay liner or other compacted soil components. Extremely low temperatures (i.e., freezing conditions) during construction of the landfill site also impact soil workability and permeability. Temperature levels also affect the installation of flexible membrane liners, in particular seaming requirements.

Weather conditions also have an impact on the performance and operation of the facility. This is particularly true in economically developing countries where heavy rainfall often results in extremely muddy access roads and unloading areas, thus leading to long delays. Extremely high precipitation also has an impact on the water table. An excessively high water table may increase the groundwater pressure on the sidewalls of a trench operation, resulting in unstable conditions and landslides. One of the more effective means of managing high rainfall is to construct and maintain drainage canals on the periphery of the site to divert water from the wastes. In the event that the site is relatively flat, one option is to design relatively small and well contained cells properly sloped for the collection of the leachate. Another alternative is to install leachate collection systems to control some of the problems associated with copious precipitation. However, the leachate collection system also must have the capacity to absorb the high flow rates, otherwise the liquid pressure in the facility will increase. High liquid pressure may result in migration of water and leachate from the site. Decreased soil density, which may cause liner instability, may also result from heavy precipitation.

On the other hand, very dry environmental conditions may make the soil hard to excavate or compact. Furthermore, in the absence of moisture, organic matter does not readily decompose. In arid areas, evaporation generally is greater than rainfall. Consequently, very little or no leachate is formed from the waste after disposal. Landfills in arid and semi-arid regions may be operated without liners and leachate collection systems. In fact, it has been suggested that the best sites for landfills are in arid regions [30]. Excessive drying of the soil used in the cover or bottom liner during construction can lead to the unwanted formation of cracks and increase the permeability of the soil.

Freezing temperatures may cause stockpiles of soil to freeze and become unusable. In extreme cases, very low temperatures may affect the proper operation of site equipment as well as the main components of the leachate collection system that are located above the frost line. Efficient operations require that operational problems of this nature be anticipated and contingency plans be developed in order to address the problems satisfactorily. Table XIV-2 lists problems due to inclement weather and potential means of managing them.

I3. SELF-HAUL

The majority of waste disposal sites allow the discharge of wastes by private individuals. These individuals are known as self-haulers. Typically, medium- and small-size vehicles comprise a considerable portion of the traffic. These users (either small haulers or private individuals) usually are not familiar with practices at the site, can damage their vehicles, can cause delays at the working face, and may cause accidents.

Some options exist for managing vehicles operated by self-haulers. The operation of the vehicles can be directed to designated areas of the working face, remote from the large collection or transfer vehicles. Alternatively, some type of transfer system can be implemented. Transfer systems commonly used consist of strategically located large self-dumping trailers. The loaded trailers are periodically towed to the working face, and emptied. Other possibilities include the use of dump trucks or roll-off containers. Normally, a platform is constructed to facilitate the unloading of small quantities of waste into the large containers.

Table XIV-2. Inclement weather practices

Problem	Method of Management
Wet Weather	
Access roads are muddy	• Add cinders, crushed stone, or demolition debris • Maintain a special working area that has permanent roads
Unloading area is muddy	• Stockpile well drained soils and apply as necessary • Keep compactive equipment off area by unloading and moving refuse perpendicular to area • Grade unloading area slightly to permit runoff
Soil is wet/unworkable	• Maintain compacted, sloped stockpiles and/or cover with tarpaulin
Soil permeability/density varies from design	• Do not compact soils in overly wet weather • Cover the soil
Leachate collection system clogging from runoff and sedimentation	• Add barriers for fines • Periodic cleaning of pipe network
Dry Weather	
Soil is dry -- unable to excavate and increased permeability	• Cover the soil to prevent drying • Moisten the soil
Cold Weather	
Soil freezes	• Insulate stockpiles with leaves, snow, or straw • Add salt to the soil • Continually strip and cut soil • Maintain well drained soil/sand • Use hydraulic rippers on frozen soil

The transfer point should be located inside the gate and as close as possible to a good access road. This area should be located such that it can be continually monitored by site personnel. For the most advanced areas of developing countries, the alternative to continuous direct monitoring would be the use of closed circuit television. If utilisation by self-haulers is high, an employee may need to be permanently assigned to the site to supervise and operate the facility. A resource recovery operation (drop-off centre) can also be added if supervision is available. Transfer facilities are oftentimes the source of problems, especially from abuse by the users. Litter is a common problem and fires may take place in the container(s). Nevertheless, the value of some type of transfer system usually is justified in terms of simpler and safer operations at the working face, improved public relations, and reduced roadway costs.

I4. SALVAGE/scavenging

Scavenging or uncontrolled sorting through raw wastes to recover materials that may be reusable is a common practice in most developing countries. This practice is strictly prohibited at the working face of a landfill in industrialised countries because there is a high risk of injury and a potential health hazard to the scavenger. In locations where regulations allow controlled salvaging, the practice can be conducted (as discussed in another subsection) away from the working area by individuals under direct supervision of the operator. Salvaging operations and storage must be confined to a specific area or facility so that they will not interfere with landfill operation. Strict controls must also be established on the types of materials that can be recovered, location and type of storage, and removal frequencies so that nuisance conditions do not develop. The individuals working in the salvaging area should be provided with uniforms, hard hats, masks, boots, and basic sanitation services. Additional information regarding the design of resource recovery facilities is provided elsewhere.

I5. WASTE receipt and vehicle routing

Every landfill site should have only one entrance and that entrance should be carefully controlled. A controlled entrance enables operators to: 1) keep records of weights or volumes of incoming loads, 2) direct incoming vehicles to a particular area, and 3) reject materials that cannot be disposed on the site. A sign should be placed at or near the entrance. The sign should clearly indicate applicable regulations, operating hours, user fees, emergency telephone numbers, permit information, and other relevant information.

Keeping control of the quantity and general types of wastes received at the site allows operators to evaluate the efficiency of the operation in terms of land use and compaction. These records also allow the operator to predict, with a certain degree of accuracy, the remaining capacity for the site. Remaining site life can be calculated with the help of topographical or aerial surveys. Aerial surveys may be unnecessary and too costly in some locations. In addition, a good understanding of the quantity and types of wastes reaching the site is very useful in determining user fees. There are various methods to monitor the quantities of waste received. Most large, modern landfills use a truck scale. Although it is preferable to monitor weights, small sites may decide to simply record volumes. If a truck scale is not available, weights may be obtained through a survey, over a short term, using a scale located away from the site. The results of the survey can be used to develop user fees and to estimate waste receipts over an annual period. This method does not take into consideration any changes in the characteristics of the waste stream.

I6. SPECIFIC operational procedures in a sanitary landfill

There are three basic operational procedures that depend on the method of landfilling. The procedures are: 1) site preparation, 2) traffic flow and unloading, and 3) waste covering and compaction. These procedures are presented as a function of the two basic methods of landfilling -- area or trench.

The sequence and method of operating a sanitary landfill are dictated by a number of factors that are specific to a site. Some of the most important factors include physical site characteristics, types of waste, and the rate of receipt of waste.

As has been previously indicated, the main difference between the trench and area methods is that the trench operation employs a prepared excavation and, as such, confines the working face between the two sidewalls. The area method, on the other hand, does not use extensive surface preparation. The width of the working face for the area method is, theoretically, unlimited. Sometimes, landfills utilise both methods, depending upon the specific circumstances. For example, initial disposal operations may utilise a trench design and, subsequently, the area method may be used on top of the completed trench fill. There are some variations to the two basic methods; they include progressive slope, progressive trench, and the cut and cover approach.

The specific operational features of the area method are described first. Many of the features that characterise the area method also characterise those of the trench method, as well as the other less common methods of landfilling.

I6.1. Area method

As previously indicated, the area method typically is used in natural depressions, in prepared areas, or on top of filled trenches. The subgrade may consist of either natural soil, a prepared surface using liners, or compacted soil or soil supplements. The use of any of these materials depends upon local regulations and design preferences. Area fills generally use the land more efficiently than trench operations. Area fills, on the other hand, may require imported soil for liners and covers.

I6.1.1. Site preparation

The primary objective in preparing a site for an area fill is to use most of the available soil that meets the design requirements. At the same time, site preparation should keep to a minimum disturbance of natural soil and vegetation. In order to accomplish these objectives, it is necessary to conduct a comprehensive inventory of the amount and type of soil available.

Excavations should follow a particular sequence so that the soil that is removed can be used elsewhere onsite, preferably without resorting to stockpiling. This procedure eliminates double handling and increased costs. A model has been developed to provide assistance in the planning of soil movement [27]. However, stockpiling a certain volume of soil is frequently necessary in order to take full advantage of the various types. For instance, topsoil should be stockpiled for use on roads, as daily cover, or for the construction of leachate collection systems or surface drainage systems. Clay may be selectively excavated and used as liner material, dikes, interim and final cover or, if necessary, used to supplement subgrades.

Soil that is stockpiled should be placed in specific areas, compacted, and appropriately sloped to maintain it as dry as possible. Soil should be stockpiled as close to the location where it will be used as practical. Stockpiles should never be placed in areas where they will interfere with traffic, cover soil that might be needed for other functions, or impede the function of drainage control systems.

I6.1.2. Traffic flow and unloading

The general procedure for managing the waste at the gate is discussed elsewhere. The procedure is applicable to both the area and trench methods.

The procedures for spreading, compacting, and covering the waste can be facilitated by controlling the position of the collection vehicles during the unloading process. If the collection vehicles are directed over previously filled areas, the areas should be well compacted. When possible, demolition debris and other dense rubble should be placed to take advantage of the drainage plan. Roads should be designed and built such that they do not interfere with stockpiling or soil handling.

The working face should be as narrow as possible without interfering with normal operations. The width of the working face generally is a problem in the operation of land disposal sites in developing countries. To facilitate this, an operator should be at the face of the fill during working hours using a whistle, a bullhorn, or flags to direct incoming vehicles to the desired area of the working face. Barricades and markers should be used to delineate the area that is used on a given day.

It there is a choice, it is preferable to keep the unloading area at the toe (bottom) of the working face. This is because spreading and compaction are easier and generally more effective when performed from the bottom to the top. If the unloading is carried out from the top, care must be taken to prevent the waste from being pushed onto a steep working face with little or no compaction applied until the end of the day, or with infrequent compaction performed. This type of practice is one of the more common operational ones in developing countries. In some situations, a platform is built on the top by compacting refuse and applying a layer or several layers of soil. This type of operation can lead to unstable conditions and landslides if the weight of material on the top of the slope is too great and the slope is too steep.

Unloading at the toe generally reduces blowing litter. The unloading area should be kept clean and level to prevent vehicles from being damaged or tipped. In small sites, it may be necessary to provide an unloading area that is wider than the working face. At large sites, or at sites that process large quantities of wastes in relatively short time spans, a portion of the unloading area should be set aside for unloading trucks manually. If the face of the fill is not sufficiently wide to allow for this process, manually operated vehicles may be routed to the top of the lift so that unloading does not impede the other traffic.

I6.1.3. Covering and compacting solid waste

Compaction and, in particular, covering of the waste are two important operations of a conventional sanitary landfill in industrialised countries. However, as previously discussed, there are some conditions under which the wastes may not have to be covered on a daily basis.

In general, spreading and compacting operations should be aimed at achieving proper cell density, height, slope, and width throughout the day.

The compacted density of the solid waste depends upon the following variables: 1) thickness of the layers, 2) composition and characteristics of the waste, 3) number of passes made by the equipment applying the compaction, and 4) compactive effort of the equipment. Compactive effort is primarily a function of the gross weight of the equipment, bearing pressure, and striking impact (if applicable). Although additional passes result in higher compaction, the return for the effort diminishes beyond six passes. An experienced operator should know when additional passes will result in greater compaction. In order to prevent soft spots in the fill area and eliminate uneven settling, excessively wet loads should be separated and mixed with dry materials before and during spreading. The slope of the working face also has an important influence on the compactive forces being applied on the waste. A schematic diagram of the compaction process is shown in Figure XIV-17. As shown in the figure, the effective compactive force acting on the waste is the product of the weight of the equipment multiplied by the cosine of the slope. Consequently, as the slope of the working face increases, the effective compactive force decreases and, conversely, the potential of slippage on the slope increases. There may be some situations where it may be difficult to avoid a steep slope; in fact at the end of the day, it may be desirable to have one in order to reduce the amount of cover material required and the nuisance potential. In those situations where a high in-place compaction is desirable, the slopes should be as gentle as possible. The tradeoff is need for more cover material and a larger area for the working face. An operator can perform some practical procedures in order to achieve high compaction densities. One of these procedures involves combining low-density, dry materials (such as paper or textile waste) with high-density, moist wastes (such as restaurant or market residues).

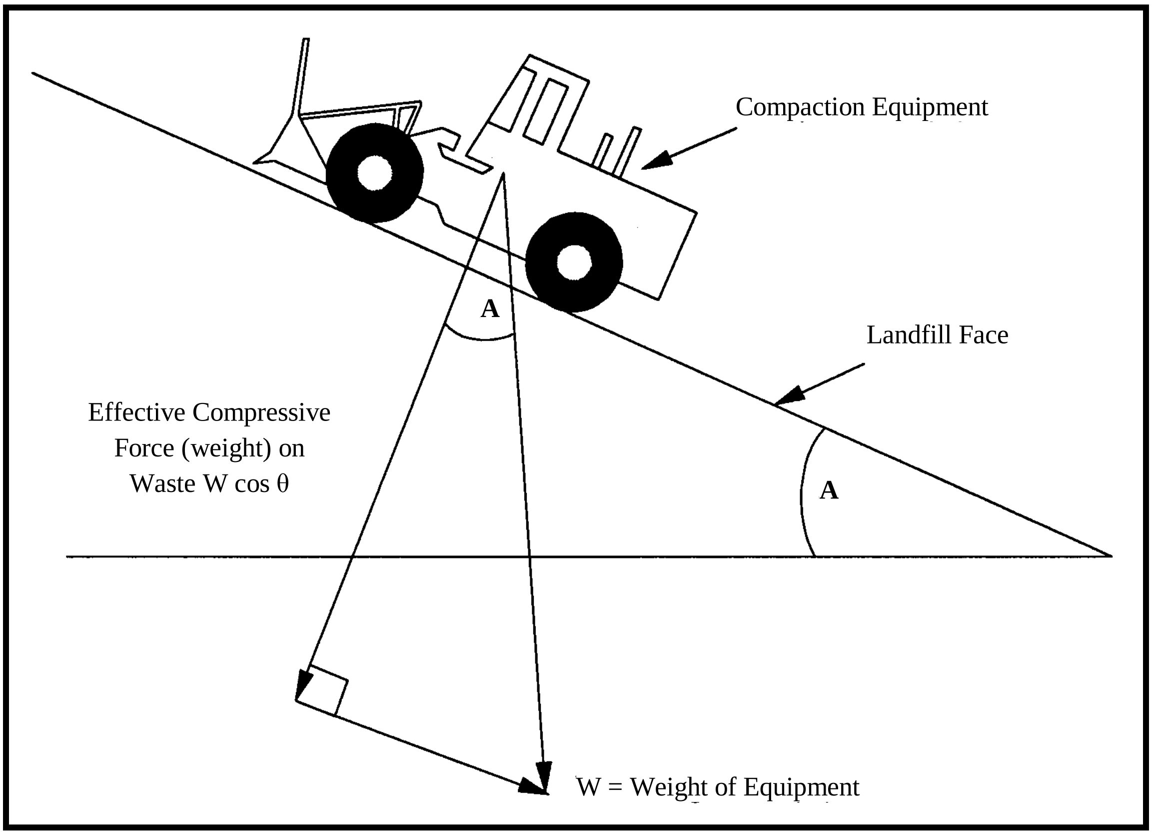


Figure XIV-17. Compaction of waste on a sloped surface

One important advantage of compaction is the increase in the capacity of the landfill. Consequently, if the plan is to optimise landfill capacity, continuous measurements of the in-place density, as well as of the remaining landfill capacity, should be carried out. Typically, the most common method of determining the degree of compaction accomplished in a landfill has been to estimate the volume of the incoming waste and either estimate or measure the in-place volume. The ratio of the incoming volume divided by the in-place volume determines the "compaction" ratio. However, these calculations simply are estimates, and they do not provide an accurate indication of the actual situation. Accuracy is particularly important in locations where disposal space is at a premium and lifespan of the disposal facility must be known to a high degree of accuracy. The most reliable means of determining the in-place density is by weighing the incoming waste and dividing it by the actual volume of the space occupied by it in the fill.

Tests can be carried out to determine the in-place density in a particular landfill and ascertain the optimum parameters to achieve the practical degree of compaction. As shown in Table XIV-3, there are a variety of variables that impact the in-place density of the refuse.

Table XIV-3. Some variables that impact the in-place density of refuse

- Characteristics of waste
- Thickness of lift
- Slope of working face
- Number of compactor passes
- Type and weight of compactor
- Design of compactor's wheel
- Condition of cell base
- Experience of operator
- Type of cover material

The final height of a lift usually is determined by the grade plan for the facility, soil usage, and operational limitations. In the case where extremely deep fills with a large number of lifts are used, the height of the lift may be limited by the equipment. For instance, a lift may be limited to the maximum height at which a scraper can provide complete coverage with one pass. Typical heights for lifts range between 2 to 4 m.

The relationships between density and the number of passes, as well as the thickness layer, are presented in Figure XIV-18.

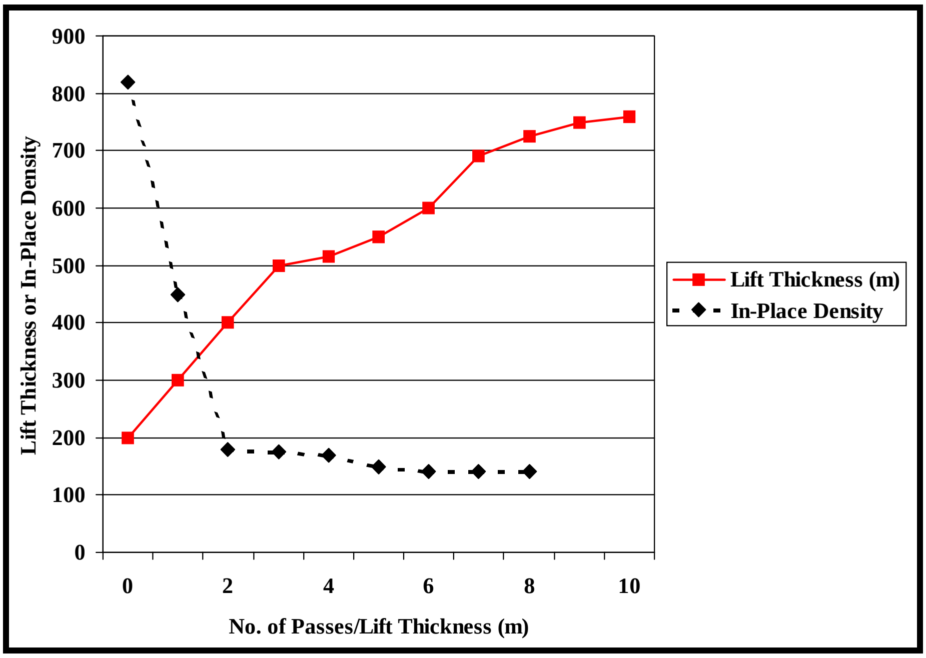


Figure XIV-18. Impact of compactor passes and lift thickness on landfill density

The slope of a cell generally should not exceed 20°, or about 3:1 (horizontal:vertical), and should never exceed that which results in structural instability of the mass. The slope should be established with initial loads and maintained constantly throughout the day.

As discussed earlier, there are three types of soil cover: daily, intermediate, and final. The thickness of each type depends upon the duration of exposure to the elements, as illustrated in Table XIV-4.

Table XIV-4. Thickness of cover soil and exposure time

Type of Soil Cover	Minimum Thickness (cm)	Exposure Time[a]
Daily	15	0 to 30 days
Intermediate	30	30 to 365 days
Final	60	> 365 days

[a] Length of time cover material will be exposed to wind and rain.

The stockpiling of soil for covering and the method of application of the soil should be performed such that the cover will not be littered with waste. These goals can be achieved by depositing the cover material at the top of the cell or adjacent to the working face. At the time that the cover is applied, the spreading equipment should only travel over the cover. The equipment should not travel through refuse onto fresh cover because this tends to draw waste on top of the cover material. The tires for the various types of equipment should be cleaned of waste before applying or compacting the cover.

Scrapers and draglines are the most frequently used types of equipment for the application of cover material. Scrapers reduce the amount of double handling. Unfortunately, the tires may be damaged by the waste materials. Draglines can also be used for the application of cover material. The use of draglines, however, requires additional grading and compacting of soil. Regardless of the placement method, the cover should be compacted and smoothed. Typically, two passes using appropriate equipment will provide sufficient compaction for daily cover soil.

The main purposes for applying daily cover are to control vectors, litter, door, water infiltration, and, to some extent, fire. The solid waste should be compacted immediately prior to placing the daily cover. Compaction of the waste will level the site and facilitate both covering and subsequent operations by providing a smooth surface. If soil is used as cover material, a minimum compacted thickness of 15 cm is sufficient to accomplish the objectives. The thickness may exceed 15 cm if a greater depth is required to cover all of the waste. Cover should be applied to the top and side slopes as cell construction progresses. This procedure serves to control generation of litter, and also results in the working face only requiring cover at the end of the working day [29]. Experience has shown that materials other than soil may be safely used to cover the waste. Some of these materials include: composted or partially composted yard wastes, the fine residues of construction and demolition debris, dredge spoils, and other materials. Designers and operators of sanitary landfills in developing countries should conduct their own evaluations of potentially suitable materials for daily cover.

Intermediate soil cover has the same general function as daily cover. The intermediate cover, however, remains exposed to the elements for a longer period of time than the daily cover. The intermediate cover may also serve as a temporary surface for traffic movement. In fact, it generally is recommended that traffic move on intermediate surfaces in order to continue the compaction process. The minimum compacted depth for an intermediate cover is 30 cm. This cover should be placed on the lift surface as soon as possible, but kept a sufficient distance away from daily activity to prevent littering from equipment moving over it.

Completed areas should be covered with a final layer of soil as soon as possible. It generally is recommended that the final cover have a minimum thickness of 60 cm. The depth and type of soil to be used and the compaction requirements should be specified in the facility design and operation plan. All but the upper few inches should be compacted in order to keep the soil permeability as low as possible. Topsoil should be added to the surface of the final cover. Seeding, mulching, fertilising, and pH adjustment should follow final covering. An EPA publication provides useful information on standard procedures for planting vegetation on final covers [28]. A separate discussion of cover systems is presented earlier in this chapter. Soil used as final cover should not be applied when it is too wet or frozen. A certain amount of soil should be saved after site completion to facilitate any grading that may be required to maintain an even surface. Completion should be phased such that once the final cover is applied, no traffic should be permitted on the completed area.

I6.2. Trench method

The trench method is most applicable on flat or gently rolling ground with deep soils. The widths and depths of the trenches can vary substantially from site to site. Trench operations usually result in excess soil and provide lateral confinement at the operating face. For a given level of productivity, a trench operation may require more land and equipment than an area operation. In addition, trench operations may need extensive soil stockpiling and handling.

I6.2.1. Site preparation

Generally, the depth and width of the trench are specified in the design and operation plans. The excavation of the first trench and also portions of later trenches may require stockpiling of large quantities of soil. The stockpiling must be conducted such that it will allow the soil to be available for use as liner and/or cover material and will not interfere with the fill operation.

As previously indicated, the size of unexcavated areas between trenches depends upon the depth of the trench and the characteristics of the soil. In general, the more cohesive and stable the soil, the less distance that will be required between the trenches. On the other hand, as the depth of the trench increases, more distance, in general, will be required between the trenches.

The amount of soil handling and stockpiling can be reduced by following either of two approaches. The first approach is called the phased fill and covering. This approach uses soil from a trench being excavated to provide cover for an adjacent trench that is in the process of being filled. Soil from the first trench must be stockpiled. The second approach is known as the progressive trench. The progressive trench method uses soil excavated from one end of the trench as cover material for waste deposited at the other end of the same trench.

I6.2.2. Traffic flow and unloading

The working face in a trench operation usually is more sharply defined than in an area operation. In the trench method, waste may be discharged over the edge (i.e., lip) of the excavation or from within the trench. Operational procedures must be developed according to the method of discharge. Stability of the sidewall is critically important if the unloading is going to take place from the edge of the trench. In addition, allowances must be made to prevent the vehicles from falling into the trenches. Typically, logs or poles are placed near the edge of the trench. A spotter should be present during unloading operations.

It is preferable in a trench operation that the waste be discharged from within the trench. In this particular case, a ramp leading to the base of the trench should be built, and maintained at a grade appropriate for vehicle traffic. Contingency plans should be provided during wet weather or when other situations make the ramp hazardous or difficult to use.

Traffic control for unloading of waste in the trench operations is similar to that for area fills. Likewise, waste handling practices described earlier for the area method also are common to trench operations, except for some special circumstances. The walls in the trench help control the width of the face and size of the cell. On the other hand, the walls of the trench can interfere with compaction if the side slope is too steep for the wheels or tracks to reach the side and still maintain blade clearance.

Narrow trench operations may experience a rapid buildup of waste during peak periods of deliveries. In such situations, adequate compaction cannot be obtained if the waste is discharged on the face. In order to prevent this undesirable situation, it is best to loosely compact the waste in the trench, and spread and compact it thoroughly when time permits.

I6.2.3. Covering and compacting solid waste

Soil cover should be placed at the same times and depths as specified for the area method. When an area fill is placed on top of a trench fill, the operation should be phased such that the area fill is commenced as soon as possible after the completion of the trench fill. This procedure will help to prevent loss of soil and to achieve the desired ratio of soil to refuse. Sufficient soil for cover should be made available from the trench operation so that area lifts on top of the completed trench fill will have adequate cover.

J. Water management

The two primary types of water resources to be protected from landfill operations are surface waters and groundwater. Surface waters may be contaminated by runoff or leachate from the landfill; whereas, groundwater may be polluted by leachate. The primary objective is to directly and indirectly prevent the landfill from adversely influencing flows to the water resource. This is best accomplished by excluding from the water resources any inputs that originate in the landfill.

J1. SURFACE water

The first step in proper water management is to minimise surface waters entering the sanitary landfill. Upland drainage can be accomplished by means of pipes through fills that are located in gullies, ravines, and canyons. Runoff from areas surrounding the fill can be excluded by excavating a series of channels or shallow ditches to collect and divert the runoff.

All runoff from the disposal site and the fill itself must be excluded from all unaffected water resources. This is done by channelling the runoff to a collection and storage site, where the runoff can be treated. Ultimately, however, the best recourse is to exercise careful control over the amount of water subsequently retained on the fill site and the length of time the runoff is retained there. The longer the retention time, the greater the opportunity for the water to be contaminated before it leaves the site. Since runoff from the fill itself occurs only when the upper surface of the fill is as high or higher than the level of the surrounding land, an effective means of minimising the extent of degradation of the runoff is to shorten the time it is retained at or on the fill. Grading the landfill cover promotes efficient runoff of rainfall. The grade of the cover should be determined on the basis of the planned use of the completed site and of the ability of the cover material to resist erosion.

Surface water that runs off stockpiled cover material should not be allowed to enter watercourses without having been previously intercepted and ponded to remove settleable solids. A complete surface water plan must be developed with other preparatory planning for the site.

J2. GROUNDWATER

The basic premise of the protection of groundwater quality is that landfilled solid wastes and any leachate from the wastes not be allowed to come into contact with and, thus, contaminate groundwater. Leachate and leachate formation are described later in this chapter. In short, leachate is generated by the passage of water through the solid waste in a fill. If moisture is already present in the fill, it is termed primary leachate. If the moisture comes from rainfall infiltrating into and percolating through the fill, the leachate is termed secondary leachate. In both cases, the eventual composition of leachate is a function of the type of solid wastes deposited in the fill, age of the fill, and several other factors.

The degree of required separation of waste from the groundwater is determined by the potential of the leachate for contaminating the groundwater. The risk of contamination is greatest when the leachate contains toxic and hazardous compounds and/or when underlying material is highly permeable. The degree of separation necessary to protect groundwater quality increases with the potential for contamination. One should not plan on the leachate being diluted in the groundwater because the usually laminar pattern of groundwater flow allows very little mixing to occur in an aquifer.

A preliminary step in protecting groundwater quality is to ensure that a suitably thick layer of soil is between the bottom of the fill and the groundwater. The interposition of the layer permits some attenuation of leachate that percolates through the layer. However, in recent years, the fund of knowledge and the depth of the understanding of leachate and its contaminating characteristics have revealed the limitations of natural attenuation that takes place in the soil layer.

J3. WATER balance and the formation of leachate

The rate of production of leachate can be calculated by performing a water balance. A water balance involves an accounting of all of the sources of water entering and leaving the landfill, including the water used in biochemical reactions and water leaving the landfill in the form of water vapour in the landfill gas. The quantity of leachate that could potentially be generated is that which exceeds the moisture-holding capacity of the material in the landfill.

J3.1. Water balance

The various components of a water balance for a landfill are presented in Figure XIV-19. As shown in the figure, the primary sources of water are: water entering the fill through the cover (precipitation), moisture in the cover material, groundwater inflow, and inherent moisture in the solid waste. In addition, a small amount of water is formed as a byproduct of decomposition of the wastes. Water leaves the landfill in the form of saturated vapour in the landfill gas, and through transpiration. The remainder of the water is either stored by the waste or becomes leachate.

The vegetation on the cover utilises water to build plant tissue and results in water loss by transpiration.

The total amount of moisture that can be stored in a unit volume of soil is a function of two variables -- the field capacity (FC) and the wilting point (WP) of the soil. The FC of a soil is defined as the quantity of liquid that remains in the pore space following a prolonged period of gravitational drainage. The WP of a soil is defined as the quantity of water that remains in a soil after plants are no longer capable of extracting any more water. The difference between the field capacity and the wilting point is equivalent to the quantity of moisture that can be stored in a particular type of soil.

Since a potential major contributor to the formation of leachate is precipitation, an estimation of its infiltration into the cover is an important aspect of establishing the water balance on the landfill system. The estimation of infiltration of precipitation into the cover is one of the more complex of landfill analyses. Flow of water from precipitation in a vertical percolation layer either is downward (due to gravity drainage) or removed via evapotranspiration. A computer model has been developed for the purpose of performing the complex computations that are required to predict the amount of water that infiltrates, or percolates, through a cover system composed of layers of different characteristics. The model is called “Hydrologic Evaluation of Landfill Performance (HELP)” [12]. Other approaches also are available for estimating the amount of percolation that can be expected in a landfill, including the use of a conventional hydrological water balance.

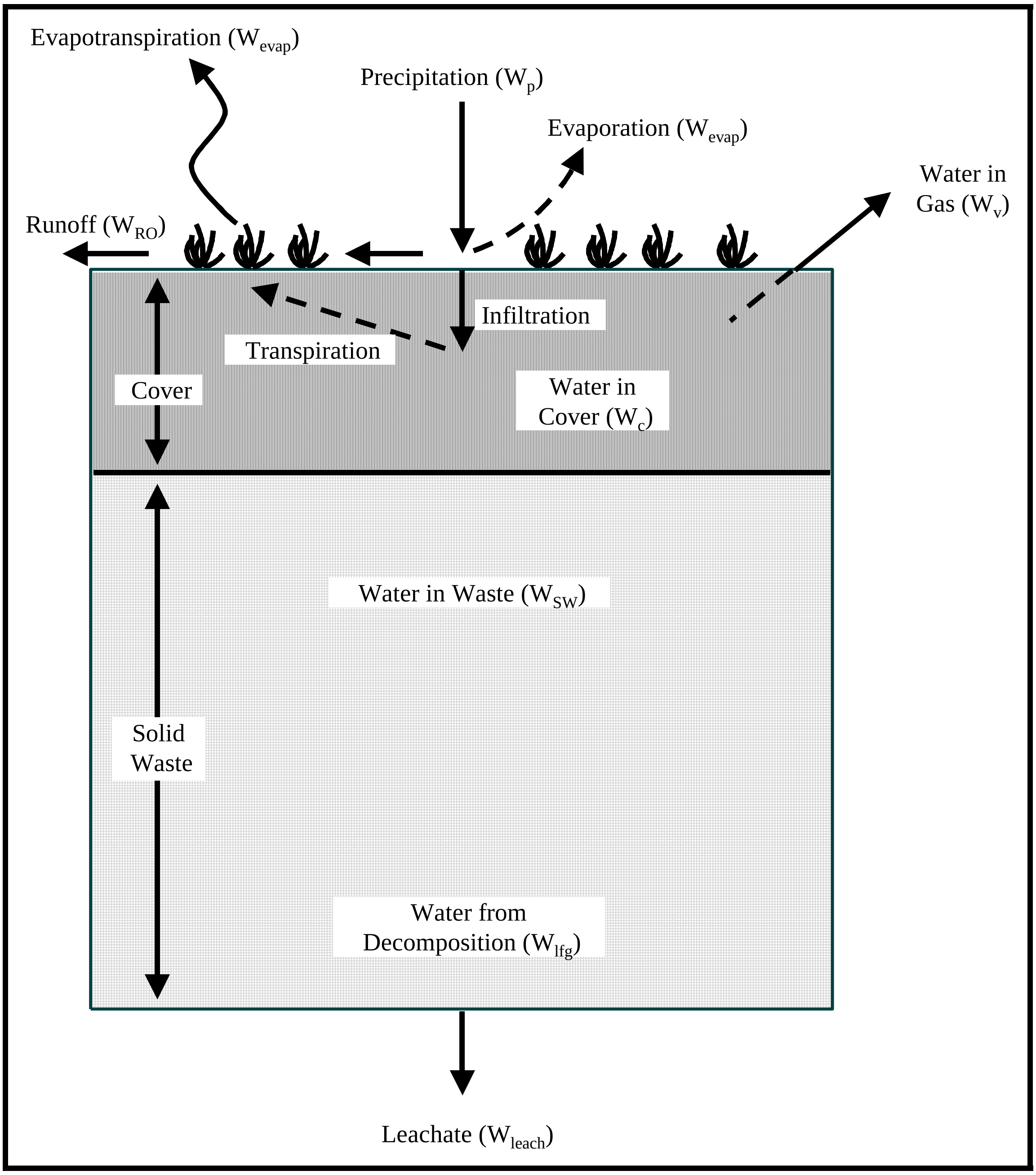


Figure XIV-19. Components of a water balance

The components of the water balance for a landfill can be expressed by the following equation if groundwater infiltration is insignificant:

$$MC = W_{sw}+W_c+W_p-W_{RO}-W_{lfg}-W_v-W_{evap}+W_{leach}$$

where:

- MC = change in the quantity of moisture stored in the landfill (kg/m^3);
- W_{sw} = quantity of water in the incoming solid waste (the moisture content of solid waste ranges from 30% to 60% in developing countries, depending on the location) (kg/m^3);
- W_c = quantity of water in the cover material (kg/m^3);
- W_p = quantity of water from precipitation and other outside sources (kg/m^3);
- W_{RO} = quantity of water from precipitation diverted as runoff (kg/m^3);
- W_{lfg} = quantity of water utilised in the formation of landfill gas (on the order of 0.2 kg/m^3 of gas);
- W_v = quantity of water lost as saturated vapour with the landfill gas (on the order of 0.04 kg/m^3 of gas);
- W_{evap} = quantity of water lost due to evapotranspiration (kg/m^3); and
- W_{leach} = quantity of water leaving the (control volume) landfill as leachate (kg/m^3).

The water balance for a landfill is prepared by adding the mass of water that enters a unit area of a particular layer of the fill during a certain time increment to the mass of water of the same layer that remained from the previous time increment and subtracting the mass of water lost from the layer during the present time increment. The result of this analysis is known as the “available moisture” for the particular layer of the landfill at that particular time. In order to ascertain if any leachate will be formed, the available moisture is compared to the field capacity of the fill. Leachate will be formed if the amount of water present (available moisture) exceeds the field capacity of the fill.

The field capacity of a landfill varies as a function of the weight of the overburden, as well as of other variables, e.g., soil and waste characteristics. The field capacity of a landfill can be estimated approximately using the following equation [11,21]:

$$FC = 0.6 \quad 0.55 \left(\frac{W}{10{,}000 + W}\right)$$

where:

- FC = field capacity, and
- W = weight of overburden calculated at the middle of the lift.

Alternatively, the field capacity of compacted solid waste, as well as other materials, can be determined experimentally. Calculated estimates of field capacity should be confirmed through measurements whenever possible.

J3.2. Leachate migration

In "typical sanitary landfills" in most industrialised countries, leachate is found at the bottom of the fill. In developing countries, where most landfills are not lined, the leachate will have the tendency to migrate in a downward motion through the underlying soils. Only a limited amount of research has been carried out on the movement of fluids through solid waste. The values reported in the literature vary from 10^{-2} cm/sec for non-compacted, raw solid waste (bulk densities of up to 300 kg/m^3) to 10^{-4} cm/sec for compacted refuse [78,79]. Depending upon the type of material surrounding the fill, it is possible that a certain amount of lateral migration will take place.

One of the major concerns associated with the uncontrolled vertical migration of leachate is the potential contamination of the groundwater. The rate of migration of leachate can be estimated by using Darcy's law:

$$Q = - K A \, dh/dl$$

where:

- Q = leachate flow rate (m^3/day);
- K = hydraulic conductivity (m^3/m^2 - day);
- A = cross-sectional area through which the leachate flows (m^2);
- dh/dl = hydraulic gradient;
- h = head loss (m); and
- l = vertical depth (m).

The negative sign in Darcy's law is due to the fact that head loss (dh) is always negative. Typical values for the hydraulic conductivity (i.e., permeability) for various soils are provided in Table XIV-5.

Table XIV-5. Typical values for the hydraulic conductivity for various soils

Soil Type	Hydraulic Conductivity, K (m^3/m^2 - d)
Uniform coarse sand	407
Uniform medium sand	102
Uniform fine sand	4
Silty sand	0.09
Sandy clay	0.005
Silty clay	0.0009
Clay	0.00009

J3.3. Attenuation of leachate characteristics in soil

Attenuation by soil is an adsorption process in which contaminants are removed from leachate moving through the soil. Attenuation is an important mechanism to consider in the design of a bottom liner and particularly if a bottom liner is not incorporated into the design of a sanitary landfill. The mechanism of removal is the adsorption of the contaminants on the surface of active soil particles (e.g., clay minerals). The fact that attenuation is an adsorption process places a high upper limit on the attenuation capacity of a soil. Hence, soil attenuation is only a short-term means of controlling contaminant migration and protecting groundwater resources from leachate. Moreover, having been contaminated by the adsorbed chemicals, the soil constitutes another source of contaminants to water percolating through the soil. In case of a need to institute corrective or remedial action, contaminated soil would have to be cleaned.

Among the chemical properties that exert an influence on the capacity of a soil for attenuating contaminants are cation exchange capacity (CEC), pH, clay content, mineralogy, free iron oxide content, and lime concentration. The attenuation capacity of a soil generally increases with increase in clay content, free iron oxide content, and lime concentration. Cation exchange capacity is largely a function of clay content and clay mineralogy of the soil. The higher its CEC value, the more efficient a soil becomes at attenuating cations and polar organics. Heavy metals frequently are held by alkali soils.

J3.4. Leachate formation in arid areas

The rate of leachate generation from landfills in developing countries located in arid regions may be relatively low if the results of a research project conducted in Lima, Peru are typical. The project was commissioned for the purpose of assessing the potential environmental impacts, including leachate production, associated with the operation of land disposal sites. The average rainfall in Lima (and generally in the entire coastal area of Peru) is less than 10 mm/yr; thus the results would be applicable to dry (arid) regions. Three micro-landfills that had been operated as sanitary landfills using sand as intermediate and final cover material and an old disposal site operated simply as an open dump were monitored and analysed. The results of the research indicate that, based on the moisture content and the field capacity of the samples and on an input of 500 Mg of waste/day, the landfills were generating between 0.5 and 1.1 L/sec of leachate [9].

K. Liners

K1. SOIL liners

To form a bottom liner for the landfill, soil can be used in one layer (i.e., a single-liner system) or in conjunction with layers of other materials (i.e., as one or more layers of a multi-layer, or composite, liner system). Hazardous wastes, due to their hazardous characteristics, require secure containment and should be disposed in sites equipped with double, or composite, liner systems. When a soil liner is used as a single liner, it reduces or may even keep the leachate from leaving the fill and reaching the subsurface environment. In the event that the soil liner is placed underneath a flexible membrane liner (FML), the soil liner serves as a protective layer for the overlying flexible membrane liner (FML). In addition, the soil liner constitutes an additional barrier to leachate migration. A soil liner must be properly designed and constructed so that it forms a long-term, structurally stable base for overlying facility components.

K1.1. Materials

To adequately serve as a liner, a soil must have a low permeability (preferably less than 1×10^{-6} cm/sec) when compacted under field conditions. After compaction, the liner should be able to support itself and the overlying facility components. The liner material should yield to handling by construction equipment. Finally, a liner constructed of the material (i.e., the soil) should suffer no significant loss in permeability or strength when exposed to waste or leachate from the waste. A soil that is deficient in a required characteristic may be rendered suitable by blending it with another soil or with a soil additive. An example is the addition of bentonite cement to decrease permeability. Ideally, the compaction and permeability characteristics of the selected soil liner material should be determined by laboratory tests, so as to provide necessary information regarding the interrelationship between moisture content, density, compactive effort, and permeability.

Of the common types of soils, a well compacted mixture containing clay is one of the more commonly used soils for a bottom liner. Clay generally refers to all soils having a particle size smaller than a given size (typically less than 2 microns). Pore-size distribution, fluid viscosity, effective porosity, and fluid density determine the permeability of clay soils to fluids. A clay liner usually is constructed as a layer 0.3 to 1 m thick. To function as an effective liner, the clay must be mixed with other granular soils and placed with the proper moisture content. The density of the liner can be increased through compaction in order to decrease the material’s permeability. During installation of a clay liner, compaction is controlled by measuring moisture content and density in each lift. If sufficient clay is not available locally, natural clay additives (e.g., montmorillonite) may be added to the mixture of clay soil to form an effective liner. The use of additives requires evaluation to determine optimum types and mixing ratios.

If it meets the necessary specifications for a liner, the native soil at the facility site would best satisfy cost and convenience considerations. Otherwise, a suitable soil must be imported from another location. Obviously, cost becomes an important consideration when offsite material is used. In developing countries, the maximum distance would depend upon local conditions. In most cases, a haul of any appreciable distance would be impractical. The liner material, whether excavated locally or imported, usually is stored as a borrow pile established at the site.

K1.2. Design and installation

Standard geotechnical practices adjusted to the geology and landfill operational requirements are followed in the design of the individual landfill liner. The soil liner must underlie the entire landfill. The liner should be of low permeability to impede leachate flow and sufficiently thick to provide a structurally stable base for overlying components. With allowances for leachate collection pipes and sump, the liner should be uniformly thick. However, the toes of sidewall slopes should be somewhat thicker to prevent seepage and to adequately join the bottom and sidewall liners (see Figure XIV-20). The liner material should be compatible with the characteristics of waste and of the resultant leachate it is supposed to contain.

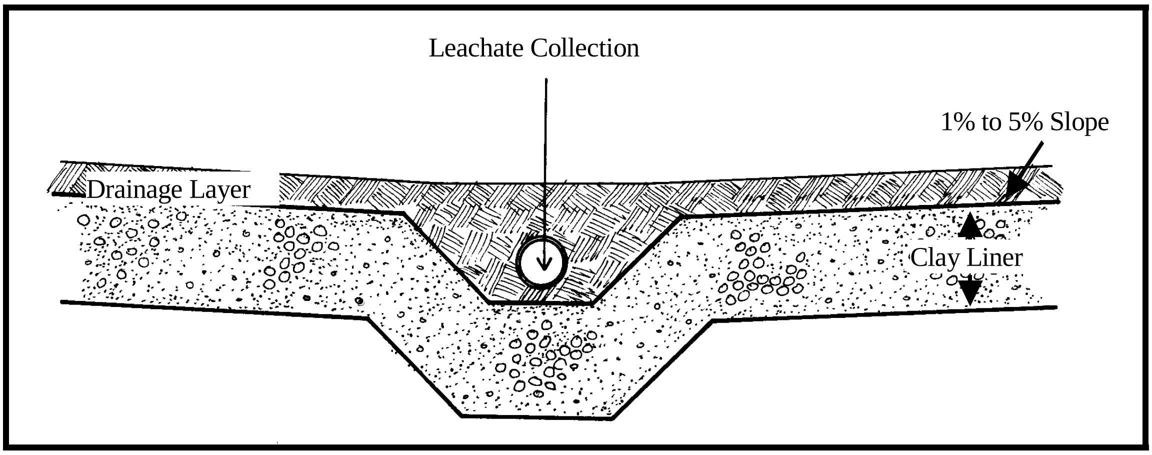


Figure XIV-20. Schematic of liner design

In general, soil liners are constructed of compacted soils installed in a series of layers of specified thickness. Although the use of thinner increments (and, consequently, more layers) facilitates compaction, it adds to construction costs because the number of layers/unit of liner thickness is increased. Generally, the thickness of liner layers prior to compaction should be on the order of 15 to 22 cm.

K1.3. Liner installation

The liner is installed (constructed) by placing the liner material (soil) with the use of scraper pans or trucks. The soil is spread evenly over the site and then is broken up and homogenised through the use of disk harrows, rotary tillers, or manually-manipulated implements to facilitate compaction. If soil additives are used, they are applied evenly over the site and then are thoroughly mixed into the soil.

The liner may be constructed in sections or in one piece. In a small facility, the liner may be constructed in one piece over the entire facility. Installation by sections probably would be more suitable with large facilities or in continuous operation facilities. In the latter operations, the wastes are placed as portions of the liner are built. It is important that the sections be installed such that no break occurs between them. This can be done by bevelling or step-cutting the edge of a section as soon as it is installed so that the succeeding section can be tied in (i.e., overlapped) with the previously installed section.

Because the necessary degree of compaction is dependent upon a proper moisture content, any required addition of moisture should be made prior to placement of the liner material. Care should be taken to distribute the moisture uniformly throughout the soil. This is done by allowing adequate equilibration time after the moisture addition. The necessary time increment may be days, or even weeks, if the soil is very dry or certain additives are used.

Practices followed and equipment used in earthwork construction are suitable for compacting a liner. The success of the compaction effort depends upon the individual liner layers being properly tied together. Tying together the layers can be accomplished by scarifying the surface of the last installed layer prior to adding the next one and ensuring that the moisture contents of adjacent layers are similar. If sidewall slopes are not very steep, they can be compacted in layers continuous with the bottom liner layers. Steeply sloped sidewalls may have to be compacted in horizontal layers because compaction equipment cannot operate on steep slopes. Tying together is especially important for steep sidewalls, because separation between layers can serve as pathways for the migration of leachate through the liner.

Because climatic conditions (e.g., precipitation, freezing temperatures, and extremely dry conditions) strongly influence activities related to soil liner construction, steps must be taken to minimise climate-related problems. For example, precipitation may interfere with construction operations by eroding or flooding the site or by over-moistening the liner material. Conversely, desiccation can cause cracks to develop in clay mixtures, with the result being unacceptably high permeability.

K1.4. Bentonite-soil mixtures

Laboratory studies have demonstrated that hydraulic conductivities on the order of 10^{-8} cm/sec can be achieved with bentonite. Bentonite can be mixed with soil to reduce the permeability of the material. The permeability of the mixture will depend upon the quantity of bentonite added, the degree of compaction, and the size distribution of the soil. If the bentonite-soil mixture is going to be used as a capping system, it is recommended to use about 5% bentonite (by wt) and a layer thickness between 15 and 20 cm. On the other hand, if the mixture is going to be used as a bottom liner, concentrations of bentonite higher than 5% (by wt) are recommended [20].

K2. FLEXIBLE membrane liners

The constituent material of a flexible membrane liner (FML) is pre-fabricated polymeric sheeting. A flexible liner may be used in many ways. For example, it may be used as a single liner installed directly over the foundation soil; as part of a composite liner placed upon a soil liner, or as a layer of a multi-element leak detection system in a double-lined landfill. In general, flexible membrane liners may be too costly to be installed in developing countries. However, should they be required, attention must be given to specifications and cost, as well as to installation.

Major steps to be taken in the use of a flexible membrane liner are selection of the FML material, designing of the subgrade, and planning the installation. The last step includes the design of subcomponents, such as sealing and anchoring systems and vents. Among the types of membranes commonly used for lining sanitary landfills are high-density polyethylene, chlorinated polyethylene, and chlorosulfonated polyethylene [4,13]. Important criteria to follow for selecting an FML include chemical compatibility with the characteristics of the leachate to be contained; possession of appropriate physical properties such as thickness, flexibility, strength, and degree of elongation; resistance to weathering and biological attack; availability; and cost.

If testing facilities are not available, judgments about compatibility of the synthetic material with wastes and leachates will have to be made on the basis of specifications provided by the manufacturer. With respect to mechanical properties, FMLs having high strength and low elongation are best suited in applications where high stresses are expected (e.g., sidewalls steeper than 2.5:1). Lower strength and higher elongation FMLs (e.g., chlorosulfonated polyethylene) are best used for applications likely to involve large deformations such as differential settlement and local subsidence. Other important mechanical properties that should be considered include: flexibility at various temperatures, resistance to puncture, thermal expansion, seaming characteristics, resistance to weathering, and resistance to biological attack and environmental conditions (e.g., sunlight and atmospheric ozone). Information on FMLs can be sought from manufacturers. Although some published literature is available, such information may be difficult to obtain in a developing nation.

The subgrade upon which an FML rests is a key factor in the maintenance of its integrity. The reason is that it serves as a supporting structure and it controls the accumulation of gas and liquid beneath the liner. Consequences of the accumulation can be uplift stress and reduction of the strength of underlying soils. In addition to those resulting from gas and liquid accumulation, mechanical stresses may be caused by subsidence beneath the liner and other stresses due to differential movements of the subgrade, etc. All of these failure mechanisms can be prevented or minimised by employing common foundation design measures to prevent settlement, subsidence, slope failure, and other undesirable occurrences, as well as other engineering design measures related to soil and liner materials.

Important design features of protective bedding layers are the provision of drainage to prevent the accumulation of gas or liquid and the protection of the liner from being punctured. The drainage layer may consist of sand, gravel, or other comparable granular material. Alternatively, it may take the form of a geotextile (a fabric designed to provide tensile strength and serve as a filter). Granular drainage layers have some substantial limitations, including difficult installation and maintenance of stability on steep slopes, and vulnerability to disturbance by workers and to erosion wind or water during construction. These problems are avoided by resorting to geotextiles. Moreover, geotextiles protect the liner from mechanical stresses.

Surface preparation for FMLs should include: 1) removal of rocks (larger than 25 mm), roots, and other debris from the surface; and 2) removal of organic materials so as to minimise settlement and gas production under the liner. Soils that expand or shrink excessively should be avoided. Finally, the substrate soil surface should be compacted to provide a firm and unyielding base for the liner. Because the actual installation of a flexible membrane liner is a complex and critical task, it should be conducted by a qualified and competent company under the supervision of the manufacturer or an engineer of the manufacturer.

L. Leachate collection and treatment

L1. INTRODUCTION

The decision to incorporate a leachate collection and treatment system as part of a sanitary landfill system in a developing country is, in many cases, a very difficult one due primarily to the expense. Obviously, the consideration only applies in those instances in which a bottom liner has been incorporated into the design of the landfill. If a leachate treatment and collection system is to be installed, funds must be available for operation as well as for capital expenses. If a thorough analysis of the situation indicates that a bottom liner and a leachate collection and treatment system should be installed, every effort should be made to implement the systems such that their construction and operation do not result in the contamination of the surrounding land resources or potential sources of water supply. The implementation of a leachate collection and treatment system involves the following design steps: 1) selection of the type of bottom liner to be applied; 2) preparation of a grading plan (i.e., channels, pipelines, and others); 3) design of the system for the collection, removal, and storage (if required) of the leachate; and 4) identification, selection, and design of the treatment system.

L2. PREREQUISITES

There are two key steps that must be carried out before a leachate collection and treatment system can be designed. The first one involves the selection of the bottom liner and the second involves the estimation of the quantity and quality of the leachate.

L2.1. Bottom liner

The processes involved in the selection, design, and installation of a bottom liner have been discussed in previous sections.

L2.2. Quantity and quality of leachate

The quantity of the leachate can be estimated based on a water balance performed on the landfill system, as has been discussed in an earlier section.

The quality of the leachate from a landfill depends primarily on the type of waste placed in the fill, degree of compaction, depth of fill, and age of the waste. For example, leachate produced during the first phase of decomposition of MSW characteristically has an acidic pH resulting from a high concentration of organic acids. Some characteristics of leachate from municipal solid wastes are presented in Table XIV-6. The range of values given in the table reflects leachates generated during the acid and methanogenic phases of decomposition.

Table XIV-6. Characteristics of leachate generated from decomposition of municipal solid wastes

Parameter	Range of Values[a)] (mg/L)
pH	4.5 to 9
Alkalinity ($CaCo_3$)	300 to 11,500
BOD (5-day)	20 to 40,000
Calcium	10 to 2,50
COD	500 to 60,000
Copper	4 to 1,400
Chloride (Cl^-)	100 to 5,000
Hardness ($CaCo_3$)	0 to 22,800
Iron - Total	3 to 2,100
Lead	8 to 1,020
Magnesium	40 to 1,150
Manganese	0.03 to 65
Ammonia- NH_3	30 to 3,000
Organic N	10 to 4,250
Nitrogen-NO_2	0 to 25
Nitrogen-NO_3	0.1 to 50
Nitrogen-Total	50 to 5,000
Potassium	10 to 2,500
Sodium	50 to 4,000
Sulphate ($SO_4^=$)	20 to 1,750
Total Dissolved Solids	0 to 42,300
Total Suspended Solids	6 to 2,700
Total Phosphate	0.1 to 30
Zinc	0.03 to 120

Source: Reference 29 for hardness, total dissolved solids, and total suspended solids; all other values, Reference 80.

[a] Range of values encompasses both acid and methanogenic phases of waste decomposition.

L3. LEACHATE collection systems

The basic purpose for installing a leachate collection system in a landfill is to remove leachate and water that may have penetrated the waste or may have come in contact with it.

The capacity of the leachate collection system depends upon the quantity of leachate expected to be generated. The system should be installed such that it is compatible with the type and shape of the bottom liner. The design of the system should incorporate every measure to minimise or prevent clogging.

One of the critical components of the leachate collection system is its drainage layer or system. The drainage layer provides a path for the leachate to flow through, thus enabling collection and removal of the leachate. In addition, the drainage layer provides protection to the bottom liner from both the waste and the heavy equipment operating on top. The drainage system typically consists of a mixture of porous materials such as sand and gravel. The materials for the drainage system should be carefully selected and graded so that they do not clog the collection pipes. Some of the more sophisticated drainage systems include more than one drainage layer. In addition, clogging between filter layers can be reduced by including a filter fabric between them.

The efficiency of the leachate collection system is partly controlled by the characteristics of the drainage layer. In particular, the hydraulic conductivity of the drainage system reduces the efficiency of the collection system. Drainage layers also are prone to clogging. Clogging of the drainage layer (i.e., a reduction in the hydraulic conductivity) results in a reduction in the quantity of leachate removed from the site.

L4. DESIGN of the leachate collection system

There are a number of proposed designs for leachate collection systems. Two of the more common systems are the sloped terrace and the piped bottom. They are described below.

The sloped terrace design involves the sloping of the bottom of the fill into a series of terraces. Generally, the recommended slopes for the terraces are in the range of 1% to 5%. This degree of inclination promotes migration of the leachate in the direction of collection pipes or channels. The collection channels typically include perforated collection pipes in a bed of packed gravel. The gravel should have a size of in the range of 3.5 to 5 cm. The gravel itself can become clogged with fine particulates; consequently, the gravel typically is enclosed within a layer of geotextile filter fabric. Usually, the inclination of the drainage channels is in the range of 0.5% to 1.0%.

The piped bottom collection system design includes the placement of clay barriers and perforated leachate collection pipes at the bottom of the site. Typically, the barriers have a defined form and a width similar to that of the solid waste cell. A geomembrane is placed on top of the clay surface. After the barriers have been installed, slotted pipes are placed on top of the geomembrane. The leachate collection pipes usually have a diameter of about 10 cm, and the perforations usually cover about 50% of the pipe’s circumference. The collection pipes are placed about 10 to 20 m apart and are covered with a drainage layer of sand and gravel. As a precaution against clogging of the pipe perforations, a fabric filter can be placed on top of the drainage layer. The separation between the pipes will control the amount of leachate that will accumulate at the bottom of the fill. In a typical operation, the layer of sand and gravel is about 60 cm thick and is placed on top of the collection pipes a few weeks before the first load of waste is discharged on the cell. It is advisable not to compact the first layer of waste in order to protect the integrity of the piping network. The slope of the unit should be on the order of 1% to 2% in order to promote the migration of leachate toward the collection points. The designs of these facilities should promote drainage by gravity [11,22-24].

L5. REMOVAL and storage of the leachate

Removal of leachate from a landfill can be carried out in either of two manners: by installing a pipe through the side of the fill or by placing a sloped collection pipe inside the fill. If a pipe is placed through the side of the landfill, the construction should be conducted with due caution in order to avoid damaging the liner system.

Most leachate collection systems will clog at some point in time. Consequently, manholes and vertical and/or horizontal cleanouts should be provided in strategic locations in order to conduct periodic maintenance and inspection.

Once the leachate is captured in a particular section of the landfill, it usually is routed to storage in tanks, vaults, or ponds. The type and size of the storage device will depend upon the quantity and characteristics of the leachate, proximity to inhabited areas, and the type of treatment required.

L6. LEACHATE management alternatives

The type and degree of treatment afforded to leachate from a sanitary landfill will have an impact on the level of pollution of any nearby groundwater and of the surrounding environment. The best approach to leachate management is to avoid generating it in the first place. However, this condition usually can be achieved or closely approached only under dry climatic conditions. If conditions are such that leachate is generated, there are several options for managing it:

- evaporation (natural or forced),
- recirculation and recycling,
- discharge to an offsite wastewater treatment facility, and
- onsite treatment.

A discussion of each of the approaches follows.

L7. EVAPORATION

Evaporation of the leachate, by natural means, is one of the more appropriate solutions for managing the leachate generated in developing countries whose climatic conditions would be compatible with the technique (i.e., high temperatures and low relative humidity). In this technique, once the leachate is collected, it is transported to an evaporation pond. The pond should be constructed using an impermeable material and should have sufficient capacity to hold the leachate plus any incident precipitation. If the pond is relatively small, it may be feasible to place a cover over the pond permanently or during the rainy season. The rate of evaporation depends upon climatic conditions; however, the evaporation rate can be enhanced by spraying the leachate either on the pond or on the surface of parts of the completed fill. Spraying on the surface may lead to generation of unpleasant odours and of aerosols that may contain pathogens and micron-size particulates, which may be of consequence if sensitive receptors are located nearby.

The rate of evaporation can be increased by heating the leachate. Heating the leachate can be a costly undertaking, although landfill gas could be used for this purpose.

L8. RECIRCULATION and recycling

Recirculation of the leachate through the landfilled wastes has been applied in several facilities throughout the world as a method of leachate management. Relatively high concentrations of BOD, COD, and, in some cases, heavy metals generally are found in the leachate soon after the waste is placed in the landfill. Under certain conditions, the potentially polluting characteristics of organic compounds in the recirculated leachate can be attenuated by the chemical and biological processes occurring in the landfill and, thus, substantial savings can be achieved in terms of the capital and operational expenses of treatment [76].

Published results indicate that a substantial reduction of the organic compounds in the leachate can occur over a short time if recirculation is employed, although many landfills that have a high rate of refuse placement have not experienced any appreciable long-term effect due to recirculation.

There are some disadvantages associated with the application of recirculation, including: 1) the potential of polluting the surrounding environment due to migration of the leachate through the sides or through the bottom of the fill, and 2) a buildup of heavy metals, salts, and other undesirable compounds in the leachate that eventually will have to be disposed.

If the landfill has two or more lifts and the lifts are capped with relatively impermeable covers, the application of recirculation should be considered very carefully. This is because intermediate covers can act as more or less impenetrable barriers, thereby leading to the accumulation of leachate on the top of the cover. Accumulation can be sufficient either to establish zones of saturated wastes, or to form water tables within the fill [33,78]. Saturation of portions of the waste can result in the material prematurely reaching anaerobic conditions and, thereby, yielding large variations in the quality of the leachate that is produced. Furthermore, the generation of areas of saturated waste above the intermediate cover can also lead to the leachate migrating to and emerging from the sides of the landfill [33,78].

L9. TREATMENT

In the event that minimisation, evaporation, or recirculation are not viable alternatives, the next viable alternative is to implement some type of treatment system. The type and capacity of the treatment system are functions of the quantity and characteristics of the leachate. As opposed to municipal wastewater, the quantity and characteristics of leachate undergo substantial variations over time. Furthermore, climatic conditions also have an impact on the quantity and quality of the waste liquid.

There are various alternatives available for the treatment of leachate. Most of these alternatives have been adapted from conventional methods of wastewater treatment. Some of the processes include physical, chemical, and/or biological steps. There are very few full-scale leachate treatment systems in operation in developing countries. A conventional design in industrialised countries would be as follows: 1) pre-treatment, 2) physical and/or chemical treatment, and 3) biological treatment. The pre-treatment step, as its name implies, generally involves a series of processes designed to prepare the leachate for further processing. Pre-treatment may include: screening, sedimentation, and pH adjustment. The second stage of the treatment includes several steps designed to remove heavy metals, suspended solids, and colour. These processes may involve flocculation, sedimentation, sand filtration, and others. The third and final general step may include a series of basically biological processes. These processes are designed to remove the organic loading (BOD and COD), as well as ammonia, from the leachate. Typical processes include: oxidation ponds, aerated lagoons, activated sludge, and others. Following are brief descriptions of some of these processes. Complete descriptions of these processes can be found in standard texts on wastewater treatment.

L9.1. Biological treatment

There are several characteristics of the leachate that will dictate the advisability of using some type of biological treatment. Some of the more important characteristics involve the relatively high organic and inorganic loads, fluctuations in the quantity, changes in the concentration of organic matter, and others. One relatively simple approach to evaluating the biodegradability of leachate is by checking the ratio of BOD to COD. If the ratio is about 0.5, then it may be possible to treat the leachate biologically. On the other hand, if the BOD:COD is less than 0.5:1, a biological system may not be appropriate as a treatment process. Ratios of BOD to COD over the course of decomposition of MSW can range from an average of about 0.6 during the acid phase to about 0.1 during the methanogenic phase [80].

Leachate contains several compounds that, in some concentrations, are known to have a negative impact on the performance of biological treatment processes. Some of these compounds are: chlorides, sulphides, ammonia, metals, and others.

Even though biological treatment processes can withstand most of the characteristics of leachate, if inhibition is observed during tests, it may be necessary to include a pre-treatment stage in the overall treatment process.

L9.1.1. Aerated lagoons

Aerated lagoons are applicable to landfills that generate relatively small quantities of leachate. In this case, the leachate is transported to a lagoon, where it is aerated by mechanical means (surface aerators or air pumps). Both aeration and the mixing brought about by the aeration enhance the degradation of organic substances by introducing atmospheric oxygen into the leachate. Retention times on the order of 10 days have produced relatively large reductions in the concentrations of BOD and COD.

L9.1.2. Activated sludge

This particular process is similar to the aerated lagoons excepting that, in this case, a certain percentage of the sludge produced in the process is recycled. As such, a settling tank is needed in the system.

L9.1.3. Facultative ponds

Facultative ponds are used to treat various types of wastewaters. The ponds generally are between 1 and 1.5 m deep and are not aerated by artificial means. In the process, the top layer of the pond behaves as an aerobic lagoon due to wind aeration and the oxygen generated by algae. On the other hand, the bottom layer is not impacted by the conditions at the surface and thus becomes anaerobic. Facultative ponds typically remove ammonia-nitrogen through nitrification processes.

Properly designed aerobic lagoons and facultative ponds may be suitable for leachate treatment in a number of developing countries.

L9.1.4. Other biological processes

In addition to the processes described in the preceding paragraphs, there are several other alternatives for the biological treatment of leachate. Some of the processes include: anaerobic digestion, anaerobic lagooning, and anaerobic filters.

In general, aerobic processes require relatively long detention times in order to be effective. Aerobic processes remove ammonia-nitrogen by nitrification or by conversion to biomass. Anaerobic treatment processes, on the other hand, probably are most applicable as a pre-treatment process since these types of processes do not remove ammonia and the effluents generally have a relatively high turbidity.

L9.2. Reverse osmosis

The application of reverse osmosis (RO) is relatively new in the solid waste management field. In the process, the liquid to be treated is forced, at high pressures, through membranes. The membranes retain impurities and a treated effluent is discharged. Due to the characteristics of the leachate, membrane fouling has been a common problem. Development of new types of membranes is addressing some of these problems. If RO is going to be used in the treatment of leachate, it is recommended that the leachate undergo some form of pre-treatment in order to reduce membrane fouling and to prolong the useful life of the system.

M. Management of landfill gas

M1. ORIGIN, composition, and volume of gases

Landfill gas (commonly termed "biogas" in some locations) is one of the products generated as a consequence of the biological degradation of the organic fraction of the wastes placed in the landfill. Immediately after disposal and for a brief period afterwards, there is enough oxygen contained in the air entrapped in the wastes so that the initial phase of biodegradation is primarily aerobic. The main constituents of the landfill gas during this stage are carbon dioxide (CO_2) and water vapour.

Waste compaction, combined with the application of the landfill cover, prevents air from reaching the wastes. Consequently, within a short period of time from initial deposition, the oxygen originally trapped in the wastes is consumed and the biodegradation process becomes anaerobic. The shift to anaerobiosis is marked by the production of methane (CH_4) and carbon dioxide (CO_2), as well as a variety of trace amounts of reduced carbon and sulphur compounds. The biological principles involved in the formation of biogas in a landfill are those that are characteristic of conventional anaerobic digestion. The principal differences are in rate of conversion of organic matter to methane and the ratio of methane to carbon dioxide. The microbiology of the decomposition of municipal solid waste has been reported in detail in Reference 67.

Typically, the composition of landfill gas is on the order of 40% to 60% CH_4, 40% to 50% CO_2, 3% to 20% N_2, 1% O_2, and traces of sulphides and volatilised organic acids. Traces of other compounds may include benzene, toluene, sulphur dioxide, methylene chloride, and others in concentrations of up to 50 ppm [15,16].

The change from aerobic to anaerobic degradation and the production of methane and carbon dioxide under anaerobic conditions proceeds as a series of phases. The first phase is the aerobic phase, lasting from a few days to several weeks -- the duration being a function of degree of compaction and other factors. The second phase begins as conditions within the fill change from aerobic to anaerobic. At this point, obligate aerobic bacteria die off and facultative aerobes shift from their aerobic to their anaerobic mode. During the second phase, CO_2 and, to a lesser extent, hydrogen are the main gases produced. The third phase can be identified by the gradual appearance of methane. In the fourth and final phase, methane production becomes constant and falls within the range of the ratio named in the preceding paragraph (40% to 60% CH_4: 40% to 50% CO_2). Research has been conducted on the identification and quantification of representative species of the microflora involved in biogasification of sewage sludge, organic municipal solid waste, and some agricultural residues [67-72]. The acidogenic population, consisting of about 90% of the total digester population, is the largest of all the groups [73]. However, relatively little is known about the number and physiological activities of the acidogenic microorganisms [74].

M2. GAS generation

Methods for estimating gas production in a conventional digester must be appropriately adjusted to reflect the differences between anaerobic digestion in a fill and anaerobic digestion in a digester (reactor). In general, the amount actually obtained from a landfill will be much less than the theoretical volumes predicted on the basis of organic waste content. Moreover, unless the fill has been specifically designed for gas containment and eventual collection, the actual yield of gas will be disappointingly small.

Municipal solid waste contains a large variety of components that have the potential to break down under anaerobic conditions. Limited data are available on the chemical composition of the various components buried in landfills. Analyses conducted between 1984 and 1987 on municipal solid waste generated in Madison, Wisconsin (United States) indicated that the material contained about 40% to 51% cellulose, 12% hemicellulose, 15% lignin, and not more than 4.2% protein [60-62]. The main components of municipal solid waste that have substantial concentrations of biodegradable fractions are: paper, yard waste, and food waste.

Along with the concentration of biodegradable organic matter, two factors that have an impact on the production of methane in a land disposal site are moisture content and pH. Studies conducted on samples from landfills indicate that the production rate of CH_4 exhibits an upward trend as the moisture content of the refuse increases regardless of age, density, or composition of the waste [63]. On the other hand, the optimum pH level for activity by methanogenic bacteria is between 6.8 and 7.4. Collecting, neutralising, and recycling the leachate through the refuse has been demonstrated to have a positive effect on the formation and rate of methane production in laboratory-scale studies [64], and in some field-scale studies [81,82]. Landfills that are operated with injection (recycling) of leachate to enhance yield and quality of landfill gas are sometimes termed landfill bioreactors.

Methane is not formed immediately after the waste is deposited in a final disposal site. In some cases, it may take months or even years before the necessary microbial populations are established and the proper environmental conditions within the fill are reached.

Change in rate of gas production parallels the temperature curve for mesophilic bacterial activity -- namely, minimal at about 5° to 10°C, and optimum at about 35° to 40°C. Between the two ranges, rate increases with rise in temperature. As such, gas production slows down considerably at temperature levels of 3° to 5°C, because microbial activity almost ceases at these levels. Consequently, in all but the semi-tropical and tropical zones, temperature may be a limiting factor during winter, early spring, and late autumn in shallow or relatively small disposal sites. Temperature would not be a limiting factor throughout the year in tropical regions or in the case of large, deep landfills, if other conditions are not limiting.

As previously indicated, rate and volume of gas production generally improve with increase in moisture level up to and including saturation. Conversely, at moisture contents less than approximately 60% to 70%, volume and rate are increasingly adversely affected by further drops. Despite a reported satisfactory gas production in a fill in which the moisture content is less than 40%, the generality holds true that in the absence of other limiting factors, gas production is best at the higher moisture contents.

Since the characteristics of the wastes and conditions vary substantially from one region to another, it follows that reported rates and quantities of landfill gas encompass a wide range of values [15,17,18,83,84]. Thus, reported gas production in landfills in industrialised countries ranges from 0.06 to 0.4 m^3/kg of solid waste disposed. Reported rates range from 1 to 10 m^3 gas/Mg of waste disposed/yr. Most of the production takes place during the 20 years following landfill closure. Landfill gas production is most active during the first 5 years or so after the majority of oxygen is depleted from the wastes (typically, 1 to 2 years). Gas production, at gradually dwindling rates, may continue for as long as 50 years.

M3. VOLUME (yield)

M3.1. Potential

The difficulty of accurately predicting a continuous production of gas at a given flowrate [75] has interfered with the attainment of an adequate knowledge of the kinetics of gas generation in a landfill. Approximations made of expected yields have a high degree of uncertainty because they are necessarily based on assumptions that may or may not prove to be valid. On the basis of volatile solids content, the maximum yield of gas would be about 0.4 standard m^3/kg volatile solids in the wastes; other reported yields are in the range of 0.006 to 0.05 standard m^3 of methane/kg of "as-received" (wet) waste [75,76]. These yields were based on data collected during the first few years of landfill operation. Decomposition generally is most rapid and extensive during this period.

Several models have been developed to predict the production rates of gas from landfills. Most of the models, however, require actual measurements of gas production in order to determine the values of constants for the models. Interest in the prediction of gas generation from wastes has recently increased due to the concern for controlling contributions to global warming. One of the predictive models is based on the following assumptions [55]:

- The main components of the degradation process, i.e., the substrate, the microorganisms, and the primary gaseous products (methane and carbon dioxide), can be quantified based on the concentration of carbon in them.

- Continuous conversion (at standard conditions) of 1 kg of organically bound carbon will yield a total volume of 1.87 m^3 of landfill gas composed primarily of methane and carbon dioxide.

In order to account for conditions typical of a disposal site, a first-order rate expression is assumed. The first-order rate coefficient is a function of temperature. The genesis of the mathematical model is the design of reactors to digest tropical vegetable material in batch reactions. The mathematical expression is as follows:

$$C_t = C_g (1-e^{-kt})$$

where:

- C_t = the quantity of gas produced in time t,

- C_g = the quantity of gas produced as t approaches infinity, and

- k = a first-order rate coefficient, in $time^{-1}$.

In order to solve this equation, it is assumed that the relationship between gaseous carbon and assimilated carbon is linear as temperature changes within the mesophilic range. The relationship is expressed as follows:

$$C_g = C_T (0.014\, T + 0.28)$$

where:

- C_g = the total carbon that can be converted to gas as time approaches infinity,

- C_T = the total amount of carbon compounds in the substrate, and

- T = the temperature in °C.

The derivation of the equation for C_g is based on the assumption that the organically bound carbon content of the waste is 200 kg/Mg.

The model using the first-order rate equation is a good initial approximation within the constraints of the assumed parameters and their values. However, the use of 1.87 m^3 of landfill gas/kg of waste and 200 kg of carbon/Mg of waste limits its application to certain land disposal sites and regions. These limiting assumptions would be particularly important in tropic and sub-tropic developing countries where the waste contains high concentrations of organic matter and typically is not covered.

A stoichiometric approach for estimating landfill gas production is described in *Recovery, Processing, and Utilization of Gas from Sanitary Landfills* [14]. This approach takes into consideration the two major classes of material that decompose to produce landfill gas. The first class consists of the easily biodegradable fraction (e.g., food waste or garbage, garden debris). The second class includes the less easily biodegradable fraction (e.g., paper, textiles, etc.).

The variables mentioned in the preceding paragraphs, as well as others, have an effect on the accuracy of models developed for predicting rates of landfill gas generation, especially rates of methane production. Among the variables for rates of methane production are volume of gas that escapes the fill, percentage of carbon that passes through the methane fermentation route, and percentage of carbon that becomes a part of microbial protoplasm. Consequently, such models should be regarded only as being approximate indicators of expected gas production trends. Actual measurements of gas flow and composition should be included as one phase of the design and implementation of a landfill gas recovery system.

Although most municipal wastes in developing countries have a high concentration of organic matter, the wastes usually are not adequately covered and thus the gases readily escape. In addition, there are several factors that affect the amount and rate of gas production in a solid waste disposal site. Some of these factors include:

- waste composition (i.e., concentration of carbon, nutrients, and inhibitors) and moisture content;
- degree of pre-treatment (size reduction, recycling, composting, baling);
- type and degree of compaction, method of operation of the landfill site, type and thickness of cover material;
- quantity of refuse, geometry, and hydrogeologic properties of the landfill; and
- climatic conditions (temperature, precipitation, evaporation, insulation).

Based on a review of available empirical information, the following can be concluded:

- The concentration of carbon in municipal solid waste can vary from 325 to 350 kg/Mg (dry basis). The amount of degradable carbon is in the range of 56% to 70%.
- Based on the results of a series of experiments conducted by the authors and other data, it can be estimated that the theoretical maximum production of landfill gas is on the order of 300 m^3/Mg of MSW (wet basis) [65].

In order to estimate the quantity of landfill gas that can be produced from municipal solid wastes generated in different countries, a multi-component model can also be used. The model uses the composition of the solid waste and the ultimate analysis (i.e., concentrations of carbon, hydrogen, oxygen, and nitrogen) of each component (i.e., paper, food waste, etc.). By assuming an anaerobic reaction, calculations of gas production and of methane are subsequently made as a function of contribution of carbon in the total MSW landfilled by component. This method has the advantages of allowing the determination of the relative contribution of each component to the overall production and composition of the gas. The method allows: 1) the development and analysis of strategies for the management of each of the components prior to landfilling, and 2) assessments of the impacts of waste composition (including moisture content) on gas production.

M3.2. Actual recoverable

The economic and, hence, practical feasibility of recovering landfill gas from a fill depends upon generation rate, conversion efficiency, and the volume of the generated gas that is retained within the fill. The volume of gas retained within a fill depends upon the extent of gas lost from the fill prior to the initiation of the recovery operation, gas loss due to migration through the cover material and sides of the fill during gas recovery, and the amount of gas remaining in the fill after the cessation of gas recovery.

Convective flow through the cover and molecular diffusion through the sides are the principal mechanisms of gas loss from a landfill. Magnitude of the loss depends upon the permeabilities of the cover, the sides, and the soil surrounding the sides. If the compacted wastes and the surrounding soil are very permeable, convective flow responding to the pressure gradient also would be a mechanism of gas movement.

The amount of recoverable gas increases in proportion to the depth of the fill, since depth is an indicator of mass of waste in place.

After a landfill has been completed, it usually is impractical to do anything further to influence the rate and volume of gas generation (However, it is possible to affect landfill gas generation (rates, yields, etc.) by injecting leachate into the fill (as mentioned earlier in this chapter) or other materials, but the system is usually installed as the fill is constructed). After completion of the fill, gas generation depends upon the nature of the buried wastes, the age of the fill, the method of operation, and climatic conditions. If the landfill uses an impermeable cover and surrounding and underlying soil layers are impermeable, the volume of the stored gas will remain intact and available for collection [45].

M4. DISPOSITION of the landfill gas

Gases generated in the fill can either be allowed to disperse and migrate beyond the confines of the fill without any effort being made to control them, or they can be collected. Collected gases may be put to some use, may be flared, or may simply be vented into the environment. Venting into the environment provides undesirable contributions to global warming. However, the collection and use of landfill gas entails significant capital and operating costs that must be compared to alternative sources of energy.

Accumulated gases and uncontrolled dispersal and migration can lead to the development of undesirable or hazardous conditions due to flammability, asphyxiating properties, and trace organic composition of the gases. The slightly positive pressure usually existing within a landfill permits gases to flow uncontrolled from the fill to areas of lower gas pressure by convective gas transport. Also, if cover is applied in an unmanaged fashion, the gas accumulated in the fill is likely to be inhibitory to the growth of roots of any vegetation that is placed on the cover.

In the absence of adequate gas control, landfill gases either migrate to the atmosphere through the landfill cover or migrate laterally through the soil around the fill until they reach areas from which they cannot escape and, as a result, accumulate. As long as the concentrations are relatively low, the gases pose only a nuisance; but when the concentration reaches a critical point, explosive levels of methane may be reached. (The explosive concentration level of methane is between 5% and 15% by volume. At higher concentrations, methane simply burns.) Because of the possibility of gas accumulation, buildings on or near landfills should not have underground structures. If such structures are present, they should be thoroughly and continuously ventilated and monitored for presence of methane.

Accumulation of gases in the fill can be avoided through the use of a porous final cover. Migration from the fill and the attendant hazards can be averted by providing an area of high permeability vented to the atmosphere. Gases flow to the surface of the vented areas where they are diluted in the atmosphere to harmless levels. The areas take the form of boreholes, of gas wells, or of interceptor trenches installed around the borders of the fill. A more useful measure is to recover (collect) the gas and use it as a source of energy.

M5. COLLECTION, upgrade, and utilisation of landfill gas

M5.1. Collection

If methane recovery is planned for a new facility, certain features should be incorporated into the design of the fill. Some of the features are characteristic of modern landfill design regardless of whether or not methane is to be recovered. For methane recovery, the fill must be effectively sealed off from the land and water environments. The steps involved in providing such sealing are the same as those described earlier. Old or existing fills should be sealed to the extent economically and practically feasible.

Gas recovery involves designing the fill such that the migrating gas can be controlled and collected. Collected gas either can be used directly as a low-heat fuel, or can be processed (purified) to form a high-heat fuel. Collection is made possible by providing a combination of strategically spaced wells and areas of high permeability through which gases are channelled to collection points. This is done by installing underground venting pipes and a gravel layer between the cover and the waste, or gravel filled trenches. The gas is removed from the landfill by way of a piping or header system to transport the gas, and blowers to pull the gas from the fill through the headers [13-15]. A schematic diagram of a landfill gas extraction well is shown in Figure XIV-21.

Proper functioning of the gas collection system is ensured through the use of blowers. The blowers are operated such that a partial vacuum is created in the headers and collection system and the gas is pulled from the landfill. Although some gas will flow unassisted into the collection wells because of the slightly elevated internal pressure of the landfill, the flowrate is too low to ensure proper collection performance. Blowers both increase the flow of gas from the landfill and broaden the effective landfill area serviced by each gas well. The blowers can be adjusted either: 1) to pull gas from the fill and discharge it at atmospheric pressure for dispersion, flaring, or combustion; or 2) to compress the gas to higher pressures for distribution or for further processing.

If the landfill has been properly operated during its lifetime, gas can be recovered from a landfill not originally designed for that purpose by way of drilling a number of boreholes into the landfill at selected gas collection points. The boreholes should be 0.66 to 1 m in diameter. Their depth should be from 50% to 90% of the refuse depth. The boreholes are fitted in the same manner as collection wells used in fills designed for gas recovery. These collection wells are described in the following paragraph.

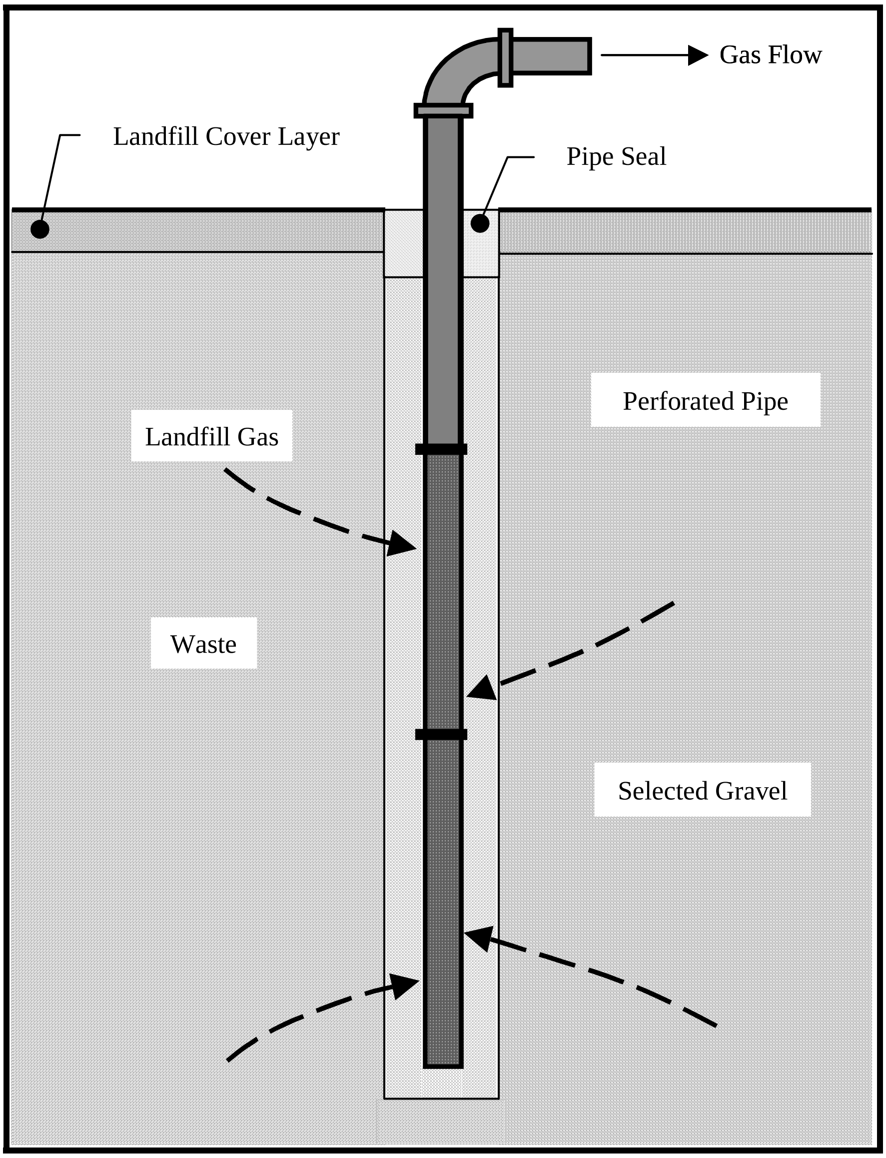


Figure XIV-21. Schematic diagram of gas well

Collection wells are gravel-packed wells equipped with casings that extend the full depth of the fill. The casings are perforated in the section exposed to the contents of the fill. The casings must have telescopic connections between pipe segments such that connections between segments are maintained despite the significant and non-uniform subsidence characteristic of landfills.

The wells are built by progressively backfilling gravel around the gas collection pipe. The backfilled gravel (or a coarse substitute) serves as a highly permeable collection zone through which the gas flows into the collection pipe for removal from the well. The gravel area is covered with a gas-tight seal topped by backfilled soil to form a barrier against intrusion of external air into the well. Air intruding into a well (or into any part of the fill) would dilute the collected gas and thereby lower its heating value and complicate purification. With respect to dilution, the concentration of nitrogen in the collected gas would be increased and the quality of the gas would be lowered correspondingly. A second, and perhaps more serious, problem would come from the presence of oxygen in the air thus introduced. The oxygen would inhibit the activity of the methane-forming microorganisms. More importantly, it may raise the concentration of O_2 to the explosive level with respect to methane.

The arrangement of the collection wells is determined by their respective capacities, as well as by the characteristics of the soil cover and provisions for directing gas movement in the fill. The dimensions of the fill area affected by a well are a function of the rate of pumping. For example, in a 12 m California fill having a gas well that was 6 m deep and was being pumped at 2.83 m^3/min, the negative pressure ranged from -5.1 cm of water at the well to less than -0.8 cm at a distance of 30.5 m from the well. Advancing the pumping rate to 8.5 m^3/min brought the respective negative pressures to -17.8 and -2.54 cm [19].

In order to avoid the problems associated with the accumulation of landfill gas, some municipalities have adapted the designs described in the preceding paragraphs to local conditions. In the example shown in Figure XIV-22, gas venting units are built by using a wooden frame, a wire mesh, and crushed stone. A landfill gas flare is fashioned by sealing the top of the collection unit and inserting a 50 mm metal pipe into the stone. A 3- to 4-L metallic can (usually a food can or a used oil filter) is welded to the top of the pipe that protrudes through the fill. Perforations are made on the side of the can, as shown in Figure XIV-23.

M5.2. Upgrading and utilisation

Unless the gas is to be used for simple space heating and household cooking, it should be upgraded before being put to use. Upgrading is essential if the gas is to be used as a fuel for an internal combustion engine, or is to be injected into existing transmission lines.

Quality and content of landfill gas do not compare favourably with those of natural gas. Moreover, its composition and other characteristics are more variable. With regard to the latter, the heat and moisture contents and oxygen concentration of landfill gas may vary as much as 50% from day to day and season to season. The heat content of landfill gases ranges from about 7,500 to 22,000 kJ/m^3; whereas the lowest heat content of natural gas is approximately 37,300 kJ/m^3. Moisture content may be as low as 5% and as high as saturation. Oxygen content varies from trace levels to levels that are potentially explosive. However, the latter levels are reached very infrequently. Finally, the usually sizeable CO_2 and N_2 contents of landfill gas materially lower its heat content and, hence, the quality of the gas.

The utility of landfill gas can be increased significantly by upgrading the gas. Among the uses for upgraded gas are onsite generation of electricity and/or injection into a public utility transmission line. Methods and procedures are available for removing H_2O (dehydration), CO_2, and N_2 from landfill gas, and thereby considerably raising its heating value.

Courtesy: CalRecovery, Inc.

Figure XIV-22. Gas removal unit made with locally available materials

Courtesy: CalRecovery, Inc.

Figure XIV-23. Low-cost gas burner

With respect to onsite generation of electricity, the gas can be used to fuel an internal combustion engine or to drive a gas turbine. The degree of cleanup of the raw gas that is required prior to combustion depends on the specifications of the engine or turbine manufacturer. Also, the gas must be delivered to the combustion equipment at the correct flow rate and pressure.

Space heating and household cooking require only that H_2S be removed. Hydrogen sulphide can be removed by passing the gas through a dry-gas scrubber that contains a mixture of ferric oxide and wood shavings ("iron sponge"). The removal capacity of the mixture is on the order of 105 kg of sulphur/m^3 of mixture. The mixture can be regenerated by exposing it to air. Doing so converts the ferric sulphide formed in the scrubbing operation to ferric oxide and elemental sulphur.

M6. USE of landfill gas in some developing countries

A few experiences have been gained in the collection, processing, and utilisation of landfill gas (LFG) in economically developing countries. In addition, some research has been conducted on the matter. Unfortunately, the results of the large majority of these efforts have not been widely disseminated nor published in international journals. Following is a brief description of some of early work on LFG that was carried out in Brazil and Chile.

M6.1. São Paulo, Brazil

The gas company in São Paulo (COMGAS) was one of the first entities to explore the potential of collecting and using landfill gas in Brazil. The company initiated a series of studies on LFG recovery in 1975. These studies were followed by actual field investigations in a disposal site (km 14.5 of Rodovia Raposo Tavares) in 1976. The field work was supported by the Petroleum National Council. After a period of evaluation, which included the collection and analysis of samples, a gas collection system was installed. The system included 13 wells; 2 compressors (capable of processing about 1,560 m^3/hr); and a network of piping connected to gas meters, filters, and condensers. The gas collected from the system was distributed to 31 residences located near the disposal site. The gas was used as a substitute to LPG [56].

M6.2. Rio de Janeiro, Brazil

Another important gas recovery project was carried out in Rio de Janeiro in 1975 by the municipal company for urban sanitation (COMLURB). The work was begun by building an experimental landfill that allowed for the measurement of important parameters of the fermentation process. The experimental landfill was operated for three years. The rate of gas production was calculated to fluctuate between 0.06 and 0.19 m^3/kg of waste. During the research, the gas was filtered, cleaned, and compressed in cylinders. The compressed gas was used as vehicle fuel [57]. In 1984, COMLURB began a landfill gas recovery system in a landfill located in Caju. Since then, several LFG recovery projects have been implemented.

M6.3. Santiago, Chile

Landfill gas has been used in the sanitary landfill of La Feria in Santiago, Chile. The gas was extracted from about 70 vertical wells. The extracted gas was mixed, without treatment, with the city gas pipeline at concentrations of up to 20% by volume. Later, the gas was treated and used as fuel in a chemical plant [58]. Other work associated with gas recovery was performed in other cities in Chile [46,59].

M7. ECONOMIC feasibility factors associated with landfill gas recovery

In terms of economic feasibility, several factors have a decisive part in determining the advisability of recovering gas from a landfill and putting it to use. Among the more important factors are size of the fill, permeability of cover material and surrounding soil layer, and proposed use of the gas. If modern sanitary landfill design criteria are followed, the permeability of the cover and surrounding soil layer should not limit the production and availability of landfill gas. Regarding utilisation, if it involves a top-quality gas, the cost of upgrading may be prohibitively high and technological infrastructure may be inadequate.

The size of the fill (i.e., mass of waste) should be sufficiently great to ensure an eventual total gas output that would have a monetary and energy value in excess of that expended on necessary departures from conventional fill practice. It would not be advisable to utilise a fill that is less than 13 m deep. The completed fill should contain at least about 2 million Mg of municipal solid waste [14]. At the peak rate of generation, raw gas production from a fill containing about 2 million Mg of MSW would be on the order of 32 m^3/min, or 760 GJ/day [14].

It is readily apparent that the proposed use of the gas exercises a decisive influence on economics and energetics. In a developing country, a safe use might be as a fuel in steam generation or for an internal combustion engine after a minimum of cleaning. Because of the relatively high moisture content and presence of corrosive elements in raw landfill gas, onsite usage of the gas is to be recommended [1].

N. Equipment

N1. BASIC concepts

The construction of a sanitary landfill requires proper equipment, suited to the work to be done, and typically involves a large capital investment. Equipment acquisition accounts for a large fraction of this investment. Furthermore, equipment operation and maintenance usually account for a large portion of the operating costs. Equipment selection must be in accordance with the landfilling method, and with the amount and efficiency of the machinery to be used in order to ensure successful operational and least-cost procedures. The requirements must take into account the handling, compaction, and covering of the solid waste, as well as the construction of cells and the completion of general earthwork. These activities must be conducted in accordance with the sequential scheme of the work scheduled. The following basic items will be considered: 1) spare equipment, 2) multi-purpose equipment, and 3) maintenance and repair [2,3].

1. **Spare Equipment.** The recommended rate of backup equipment capacity is about 30%. This percentage is applicable to the total amount of work hours resulting from the design of the landfill operation, considering a maximum of 20 hr/day for the operation of heavy machinery. For instance, if the design specifies two machines operating a total of 36 hr/day, a 30% backup capacity factor dictates that three machines be available. Although the purchase of spare equipment will strain the initial capital investment, it will assure the continuity of service and extend the useful life of the machines.

2. **Multi-Purpose Equipment.** One way of balancing the cost of spare equipment is through the use of multi-purpose equipment able to perform more than one task. An example is a landfill compactor that can be utilised for either compaction or covering of solid waste, and for building haul roads. This strategy demands that the time requirement for each particular task and equipment be carefully determined and scheduled. The use of multi-purpose equipment does not supplant the need for spare equipment.

3. **Maintenance and Repair.** Maintenance and repair require detailed planning in order to satisfy the need for continuous service. These tasks should be performed in the field in order to avoid the inconvenience and loss of time attending the hauling of broken down equipment to a remote workshop. Cleaning of all the rolling stock assigned to the handling of solid waste is required on a daily basis. Cleaning must include removal of soil and wastes from the critical rotating and heat transfer systems of the equipment so friction and overheating do not contribute to premature equipment failure. Inspection, cleaning, and washing of the machines' radiators should be performed regularly for all rolling equipment that come into contact with solid waste. This operation should be performed daily, unless circumstances dictate a higher frequency. Other maintenance operations, described in the corresponding equipment manuals and/or catalogues, must be scheduled in advance and performed according to the manufacturer's specifications. The necessary tools and a complete set of manufacturer-recommended spare parts should be readily available at the site for the conduct of light and medium mechanical repairs.

N2. FACTORS

In addition to the obvious factors of suitability of particular equipment to landfill construction and operation and the probable multiple use of that equipment, three important factors enter into equipment selection:

1. amount of waste to be landfilled and the type of materials to be handled;

2. economic feasibility; and

3. availability of maintenance and repair facilities, and skilled personnel to perform the tasks.

However, failure to take into account any one of the three factors makes successful long-term operation of a landfill virtually impossible.

Maintenance and repair are especially important in developing countries. With the exception of the smallest of operations, a landfill involves a large amount of materials handling (soil and solid waste). Because practicality sharply limits the amount of wastes and soils that can be handled manually, most landfill operations must rely on mechanisation. Regardless of the ruggedness of the equipment, it will break down under the rigors of landfill operation unless it is conscientiously maintained.

The need for conscientious maintenance takes on added significance in developing countries because replacement parts often are difficult to obtain. This situation is made worse by the scarcity of personnel skilled in the maintenance of heavy equipment.

N3. FUNCTIONS served by equipment

Basic functions served by landfill equipment fall into the following three categories:

1. functions related to soil (excavation, handling, compaction);
2. functions related to wastes (handling, compaction); and
3. support functions.

Depending on the size of the operation, the same piece of equipment potentially can be used for more than one of the three functions.

N3.1. Relative to soil

The excavation, handling, and compaction of soils used as liner and cover material are considerations when determining the function of the landfill equipment. Procedures and equipment for accomplishing those tasks differ only slightly from those used in other earth-moving operations. Consequently, the degree of mechanisation and sophistication of equipment suitable for sanitary landfilling in a given situation would not differ markedly from that which is characteristic of other earth-moving operations in that area. This limitation extends to the procedural and equipment variations to meet specific requirements due to local topographic and soil conditions. For example, wheeled equipment usually is satisfactory for excavating soils in which sand, gravel, clay loams, and silt loams are the predominant constituents. On the other hand, tracked equipment would be indicated for the less workable soils.

N3.2. Relative to wastes

Functions served by equipment relative to wastes are distribution, spreading, and compaction. With small-scale operations, and those sharply constrained by inadequate economic resources, the equipment used for earth moving is adequate for the waste handling functions. Distribution can be accomplished by confining the unloading of collection vehicles to the immediate vicinity of the working face and, thereby, combining distribution and spreading. This dual function can be done by means of the bulldozer used to move and spread soil, and for compaction.

The compaction activity demands full attention because of its many short- and long-term effects on the operation of the landfill and rate and extent of settling, but mostly because it is an important determinant of landfill capacity. Heavy equipment specifically designed for compaction would be more effective and efficient for this function than would be a piece of lightweight equipment designed primarily for earth moving. However, lack of substantial machine weight (or, more correctly, applied pressure) can be offset significantly by increasing the number of passes over the waste mass.

Landfill equipment must be rugged because operational conditions for equipment used at the fill are far from ideal. Radiators tend to become clogged and damaged, and the body and operating parts of the equipment can be damaged by protruding or dislodged wastes. Tires, even heavy-duty types, can be punctured or cut, which results in a short lifespan. This combination of unfavourable factors emphasises the necessity of maintaining a parts inventory and an adequate repair and maintenance facility convenient to the fill.

N3.3. Support functions

With respect to the initial and subsequent construction phases of a landfill, support equipment would be needed for the installation of environmental control measures such as flexible membrane liners and covers, a leachate collection facility, and gas vents.

Support functions during the operational phase include extension and maintenance of roads to the working face of the fill, dust control, and fire protection. Unless collection and transport vehicles are equipped with self-unloading features, support equipment might be needed to assist unloading. If labour is abundant, unloading can be done manually.

N4. EQUIPMENT types: descriptions and specifications

N4.1. Considerations

Factors that will be considered in this section are closely related to types and characteristics of the machines themselves. One characteristic that should receive careful consideration in equipment selection is the ability of the machines to perform multiple functions. More importantly, the selection should be based upon the primary function of each piece of equipment and its ability to handle those functions under the conditions peculiar to the site.

N4.2. Types of rolling equipment

The following paragraphs will deal with the main functions and characteristics of the different types of equipment used at sanitary landfills.

N4.2.1. Track-type tractors with push-blades (bulldozers)

N4.2.1.1. Function

The function of bulldozers is to distribute and compact solid waste, as well as to perform site preparation, provide daily and final cover, and general earthwork. An example of a bulldozer is shown in Figure XIV-24.

Courtesy: CalRecovery, Inc.

Figure XIV-24. Bulldozer

N4.2.1.2. Characteristics

Bulldozers are equipped with metal tracks having variable standard widths. The cleats of the tracks must be high enough to facilitate size reduction of the solid waste and to provide good traction on the slopes planned for the fill. The bearing pressures exerted on the solid waste or soil typically are in the range of 0.5 to 0.8 kg/cm^2 for track-type tractors with power ratings in the range of 100 to 230 kW.

The degree of compaction of the solid waste depends on the pressure exerted. Tracked machines are not very efficient at compacting solid wastes due to their low ground pressure.

In order to obtain maximum efficiency from a track-type machine, it is very important that it be equipped with an adequate blade to push the material. The density of solid waste is about 3 times less than that of soil; therefore, it is possible to increase the capacity of the blade. The capacity of a blade can be increased by increasing its height, e.g., by using a steel screen. A screen avoids interfering with the operator's visibility. The dimensions of the blades vary with each model. For example, a typical 100 kW machine would have a blade with the following dimensions: 3.2 m wide and 1.8 m high (with screen).

The push-blade is controlled through a hydraulic mechanism. The estimated productivity for a typical 100 kW model, on flat surfaces, is on the order of 50 Mg of solid waste/productive workhour. On sloped surfaces, the production will obviously decrease; thus, for a recommended maximum slope of 30°, production will be reduced to 30 Mg/hr for the same 100 kW model.

N4.2.2. Landfill compactors

N4.2.2.1. Function

Landfill compactors spread and compact the incoming solid waste. A photograph is presented in Figure XIV-25.

Courtesy: CalRecovery, Inc.

Figure XIV-25. Landfill compactor

N4.2.2.2. Characteristics

Landfill compactors typically are equipped with either a standard or turbo diesel engine. The metal wheels, which perform the compaction process, usually have alternated, specially designed teeth that allow them to concentrate the weight on a smaller contact surface (as compared to a track-type machine) and to exert a greater pressure on the solid waste. For example, landfill compactors weighing 16,000 to 26,000 kg typically exert a pressure of 75 to 120 kg/cm^2, respectively.

This type of equipment is more versatile and faster than bulldozers. A typical 110 kW model will have a productivity of approximately 75 Mg/hr on flat surfaces. The productivity decreases to about 50 Mg/hr for a 30° slope.

Landfill compactors are equipped with a hydraulically controlled blade. The blade may have a metal screen attachment above it to increase it’s the processing capacity of the compactor, to allow the operator to see the waste in front of the blade, or both. The blades are characteristically about 3 m wide and 1.9 m high, including the screen.

N4.2.3. Wheel loaders

N4.2.3.1. Function

Wheel loaders are designed to excavate soft ground (i.e., ground offering little resistance), load the excavated material onto trucks, and pick up or transport that material to distances not greater than 50 m to 60 m (for optimum efficiency).

N4.2.3.2. Characteristics

Wheel loaders generally are equipped with a diesel engine and four-wheel drive. The front axis is fixed and the rear axis can oscillate. Models vary in power, ranging from 75 to 280 kW. The capacity of the bucket varies from 0.8 to 6 m^3. The most commonly used models are those falling in the range of 75 to 110 kW, with bucket capacities characteristically in the range of 1.3 to 2.7 m^3, respectively.

On soft ground, a 100 kW machine with a bucket capacity of 1.9 m^3 would be able to excavate and load a dump truck at a rate of about 160 m^3/workhour. On tougher ground, the production would be less.

Wheel loaders also are able to perform efficient earthwork with clay-like soil, such as cell covering operations and preparation of sites to be landfilled.

N4.2.4. Track-type loaders

N4.2.4.1. Function

Track-type loaders can perform similar functions to wheel loaders. Track-type loaders also are able to excavate tough ground. The optimum distance for a track-type loader to transport material does not exceed 30 m.

In emergency cases, track-type loaders can be used to handle (i.e., to spread and compact) solid waste. They can also be utilised to contour and level the cover material.

N4.2.4.2. Characteristics

Tracked loaders are equipped with a diesel engine having power ranging from 70 to 200 kW. Machines having bucket capacities in the range of 1.3 to 2.5 m^3 and bearing pressures in the range of 0.8 to 0.9 kg/cm^2 typically are powered by engines in the range of 70 to 140 kW, respectively.

The bucket in track-type loaders is easily and quickly operated through a hydraulic mechanism. Better efficiency and flexibility can be achieved with this equipment when it is equipped with a multi-purpose bucket. This type of bucket performs four different operations, according to the position in which the bucket is operated. With a multi-purpose bucket, the track-type loader can function as a loader (opening the grapple will allow the material within the bucket to be totally discharged), dozer, or scraper. Additionally, the clamping capability of a multi-purpose bucket can be used to lift materials like trunks and branches of trees.

The approximate earth-moving capacities for loaders and scrapers are presented in Table XIV-7.

Table XIV-7. Approximate earth-moving capacities for average soils (m^3/hr)

Type	Capacity of Unit (m^3)	One-Way Haul Distance (m)								
		0	30	60	90	120	150	180	240	300
Tracked loader	2	80	60	45	40	35	30			
Pulled scrapers	12					165	145	125	100	75
Self-propelled scrapers	14						250	240	210	180

N4.2.5. Track-type (tracked) excavators

N4.2.5.1. Function

The function of this equipment is typically to excavate soil, excavate trenches for the placement of solid waste, load trucks, and to apply the daily or primary cover of solid waste. Track-type excavators can also be used for certain tasks in earthwork operations. An example of this type of machine is given in Figure XIV-26.

Courtesy: Caterpillar, Inc.

Figure XIV-26. Track-type excavator

N4.2.5.2. Characteristics

The excavator is equipped with a diesel engine and a hydraulic system to control the movement of the boom and that of the bucket.

The length of time of the excavation cycle depends on the size of the equipment and on the site conditions. Thus, when the excavation is more difficult or the trench is deep, the excavation procedure will be slower. The cycle time is primarily a function of the type of soil and excavation depth. For excavators with engines rated in the range of 100 to 240 kW, bucket capacities and maximum depth of excavation are in the range of 0.8 to 1.9 m^3 and 6.4 to 8.5 m, respectively (measured from the ground level), depending on the reach of the boom and the type of soil.

N4.2.6. Motor graders

N4.2.6.1. Function

This equipment is used in the construction and maintenance of hauling roads, embankments, and drainage ditches, and in the profiling and levelling of cover material.

N4.2.6.2. Characteristics

Graders are equipped with a diesel engine, rubber wheels, and power steering. The equipment typically is powered by engines with power ratings of 90 to 160 kW and gross weights of 12,000 to 18,000 kg. The standard blade for these machines is about 4 m in length and 0.7 m in height. The blade can reach a maximum slope of 90°, and is able to adopt different positions.

These machines can carry a scraper as an additional piece of equipment. The scraper is used to rip the ground to a depth of 0.1 to 0.3 m.

N4.2.7. Soil compactors

N4.2.7.1. Function

The function of soil compactors is to compact soils and embankments.

N4.2.7.2. Characteristics

Soil compactors can either be self-propelled or pulled by tractors.

Basically, this equipment performs compaction by conveying high pressure to the soil using cylindrical drums with “feet”. The drums can be ballasted with water. The average pressure depends on the design of the drum and foot, and on operating conditions. For the case of two cylindrical drums having the following dimensions: diameter of 1.53 m, width of 3.4 m, 120 feet/drum, and 12,600 kg of drum and water ballast -- the pressures exerted on the ground (over several types of foot designs) would be in the range of about 27 to 82 kg/cm^2.

Some machines have a mechanism that allows oscillation of the drums, which can facilitate uniform compaction, even on irregular layers of soil.

N4.2.8. Pneumatic tire compactors

N4.2.8.1. Function

These machines are designed to compact topsoils and sub-layers, especially when loamy material is present. High and uniform densities can be obtained throughout the thickness of the layers.

N4.2.8.2. Characteristics

Pneumatic tire compactors can be either self-propelled or hauled by tractors. The load is transmitted to the ground through the contact surface of the tires, which form the rolling unit. Typically, these compactors have seven tires.

The ballasting of the equipment is done with wet sand (density = 2,000 kg/m^3), which can reach weights ranging from 13,000 to 35,000 kg. The operation is as follows:

- Initially, low tire pressures are used in order to have greater contact areas and less compaction resistance.

- During the compaction process, the tire pressures are increased, reducing the contact area and, therefore, the compaction pressure.

These machines have a device that allows proper control of the pressure of the tires.

N4.2.9. Self-propelled vibratory drum compactors

N4.2.9.1. Function

Vibratory drum compactors are designed to effectively compact soils and cover material formed by normal soils, whether granulated or clay-like.

N4.2.9.2. Characteristics

Vibratory drum compactors have a metal drum on the front. The approximate dimensions of the drum are: width, 2.15 m; diameter, 1.5 m. The compactors have pneumatic tires on the back.

The vibration system is operated by a hydrostatic engine directly connected to the vibrator, allowing variations in amplitude and frequency, independent from the speed of the propelling engine. The vibration frequency can be regulated to reach a maximum of up to 2,000 vibrations/min.

The weight of the equipment varies according to the model (9,000 to 12,000 kg).

N5. INSPECTION and maintenance

As previously indicated, the costs associated with operation and maintenance of the equipment used in landfills account for a major portion of total costs of operation. A program of frequent inspection and systematic maintenance should be implemented in order to prevent costly breakdowns of equipment. The maintenance program should be based on guidelines provided by the manufacturers of the equipment.

Facilities must be provided for carrying out the various maintenance procedures. Facilities include garages, tools, testing equipment, and a stock of replacement parts. Equipment manufacturers should be requested to provide a list of basic replacement parts and the name and location of a source for additional parts. Ideally, the source should be located within the country.

A summary of typical equipment required to operate a sanitary landfill is given in Table XIV-8.

Table XIV-8. Suggested equipment requirements as a function of waste generated

Waste Generated (Mg/day)	Equipment			
	Quantity	Type[a]	kW	Wt (1,000 kg)
0 to 20	1	TD, TL, RTL	50 to 75	6 to 9
21 to 50	1	TD, TL, RTL, LFC	60 to 160	7 to 20
51 to 130	1	TD, TL, RTL, LFC	75 to 160	9 to 20
131 to 250	1	TD, TL, RTL, LFC	110 to 240	12 to 30
251 to 500	1 or 2	TD, TL, RTL, LFC, S, DL, WT	190 to 340	25 to 40

[a] TD = tracked dozer
TL = tracked loader
RTL = rubber-tired loader
LFC = landfill compactor
S = scraper
DL = dragline
WT = water truck

O. Provision for material recovery

O1. INTRODUCTION

This section discusses only material recovery performed at the final disposal site (scavenging), not that performed at the point of waste generation, during collection, during transport, or in a materials recovery facility. Presently, the sequence most commonly followed for scavenging at a typical disposal site in a developing country is as follows: incoming refuse is discharged at or near the working face, scavengers sort through the load, equipment spreads and compacts the residues from the scavenging activity, and the scavengers sort their recovered materials into organised portions.

Typical materials recycled in this manner include unbroken bottles, metals, plastics, cardboard, paper products, bones, textiles, and glass.

O2. PROBLEMS due to scavenging

The case for allowing scavenging at the final disposal site must be strong enough to counterbalance the objections that can be raised against scavenging. These objections stem primarily from the safety hazards to the personnel of both the scavenging group and landfill employees and secondarily from the interference caused by the scavenging activity with respect to the fill operation. The hazards posed by the intermingling of the manual scavenging activities and the equipment-oriented sanitary landfilling activity increase with the number and size of the landfill equipment.

O3. ESTABLISHMENT of scavenging site

The difficulties that arise between the landfill operations and scavenging can be substantially reduced or even eliminated by treating the scavenging activity as a first phase in a series of steps that make up the landfill activity. This approach allows a physical separation of the two activities. Unfortunately, such a separation adds a step to the overall operation. The step consists of two parts: 1) discharge the incoming wastes at the area designated for scavenging at the disposal site, and 2) transfer the residue remaining after scavenging to the working face.

If the scavenging area is established relatively close to the working face, transport of the residue from the scavenging operation may be done quickly by means of a bulldozer. This arrangement would require that the scavenging area be movable. The design of a system of this type should provide adequate separation between the two activities so that those of the scavengers do not interfere with those of the land disposal operation.

A permanent scavenging facility can also be established, although a fixed scavenging site in most cases would be neither feasible nor advisable for a small disposal site. Dedication of a fixed portion of the disposal site to scavenging takes on many of the characteristics and advantages of a transfer station. For instance, scavenging done in a fixed area can be sheltered from the elements (wind, rain, etc.), the operation itself can be kept more orderly and closely controlled, and efficiency can be improved by including a certain amount of mechanisation (e.g., conveyor belts and screens). Best of all, encounters between scavengers and landfill equipment could be limited or avoided altogether. These advantages combine to enhance efficiency. This alternative allows for the provision of much needed sanitary facilities and a better working environment for the scavengers.

The scavenging area can be located about 1 to 2 km away from the working face. In this case, the waste to be disposed would be transported by means of a truck. The size of the disposal site is the decisive factor regarding advisability and necessity for dedicating a portion solely to scavenging. In general, a minimum lifespan of 10 years would justify the incorporation of a fixed scavenging area. This option was been adopted for the management of a portion of the residential wastes generated in Mexico City, Mexico.

O4. MANAGEMENT of scavenging activity

Landfilling should have precedence over scavenging since the reason for the fill is the disposal of wastes. Therefore, scavenging must be managed in a way that does not unduly interfere with the main activity of the landfill site. On the other hand, consideration must be given to the loss of income to the scavengers, as well as the loss of secondary materials to the local industry, if scavenging were to be discontinued. In some cases, secondary materials have been shown to play an important role in the local economy [10].

Unless traffic to and from the disposal site can be carefully managed, it can be one of the more disruptive of the interfaces between scavenging and final disposal. Among the more obvious causes of disruption are the increase in number of vehicles using the same road and the different vehicular speeds that result from the different types of vehicles employed for waste hauling and by scavengers. In some instances, long delays are brought about by the discharge of recyclable materials from the waste collection vehicles. Waste hauling traffic will generally move at a much faster speed than will scavenger traffic, and will be substantially slowed both by intermingling with scavenger traffic and by the increase in traffic density. One of the better approaches to separate the traffic is to provide different access roads. Unfortunately, this is probably one of the more expensive solutions. Hence, the decision involving separation of access would rest upon economic feasibility.

O5. SUPERVISION and procedures

The scavenging activity should be under the direction of a supervisor whose principal function is to make sure that the activity proceeds efficiently and fairly, and does so with a minimum of interference with the disposal operation. Accomplishing the latter objective implies working closely with the manager of the disposal operation. The manager of the disposal operation should have the authority to make decisions with regard to scavenging activities that affect the disposal operation. Efficiency and safety demand that good housekeeping be rigorously enforced.

A relatively fixed set of procedures should be established for the scavenging activity. Procedures should be established concerning: 1) assignment of spaces and refuse loads to individual scavengers or groups of them; 2) removal of scavenged material from the site (i.e., frequency, method of loading, type of vehicle used for the removal); and 3) sale of the recovered materials

The labourers should be provided with uniforms and safety equipment, bathrooms, showers, eating facilities, and first aid equipment.

P. Environmental monitoring

Ultimately, the rationale for monitoring is to detect adverse impacts of the landfill on the adjacent air, water, and soil environments so as to be able to take the remedial measures needed to counteract the impacts. The process consists of: 1) establishing baseline environmental data and characterising the nature, extent, and magnitude of the impact; and 2) developing a remedial course of action. Impacts are indicated and identified by differences between the pre-landfill and post-landfill qualitative and quantitative characteristics of the air, water, and soil environments, or by the existence of gradations in quality and quantity with respect to proximity to the fill. Programs and methods for monitoring can range from minimal to quite extensive in terms of extent, complexity, type, and costs. The minimal category would be sufficient for situations in which the need for monitoring does not warrant an extensive program.

P1. GROUNDWATER

According to the general principles mentioned in the preceding paragraph, impact on groundwater quality can be evaluated on the basis of difference between groundwater quality (e.g., pH; dissolved solids concentration; chemical composition; and presence, identity, and concentration of microorganisms before and after construction and completion of the fill). Impact of an existing fill on groundwater flowing under and around the fill can also be evaluated on the basis of difference between the quality of the groundwater before it reaches the vicinity of the fill and after it has moved beyond the fill. Estimates depending upon groundwater flow pre-suppose a knowledge of the direction and velocity of the groundwater flow.

Potential impact on groundwater quality can be estimated on the basis of the composition and quantity of leachate generated in the fill. Knowledge of leachate composition and rate of production would also be of use in the identification of contaminants attributable to the landfill and in predicting the intensity of the contamination. To obtain such knowledge, it is necessary that the fill be provided with a leachate collection and sampling system. The problem is that in developing nations, such installations are rare and the fund of accumulated data under controlled conditions is sparse. The applicability of leachate data collected for landfills in industrialised countries must be analysed prior to considering them representative of a given location in a developing country. If a leachate collection system is available, then monitoring would consist of measuring rate of leachate production and analysing the leachate for items of interest. Examples of such items are physical characteristics, the identity and concentration of toxic chemicals and chemical constituents adverse to water quality, and pathogenic organisms.

P1.1. Monitoring wells

Because sampling (collection and analysis) is a key element in a groundwater monitoring program, the method of sampling must be carefully considered. In this connection, networks of monitoring wells play an important role. The extent and sophistication of this network are determined in part by the purpose of the program and by the economic and technological resources of the region that is to be served by the network. With regard to purpose, a monitoring well network for gross groundwater quality indicators differs drastically from wells intended for detecting toxic organic compounds or heavy metals. The wells must be installed at proper horizontal and vertical positions near the landfill.

Appropriate methods for installing the wells are determined on the basis of anticipated nature of subsurface aquifer materials, site accessibility, availability of drilling water, desired diameter and depth of the well, nature of subsurface contaminants, and economic and time constraints. (A list and evaluation of the many methods may be found in “Guidelines for the Land Disposal of Solid Wastes” [8].)

Of the various applicable criteria, all wells should, at least, meet the following two criteria: 1) water must flow freely into the well; and 2) downward migration of surface water or upward migration of undesired groundwater to the well-intake zone must be prevented. Basic elements in the design of monitoring wells are the casing, filter pack, seal, annulus backfill, and grouting. The elements are indicated in Figure XIV-27. Installation is completed by well development. Well development accomplishes two tasks: 1) the well is cleared of foreign materials introduced during drilling, and 2) the natural formation adjacent to the well screen is restored. Development may be accomplished by way of bailing, pump surging, air lifting, and combined air lifting and bailing.

Among the several methods for drilling a monitoring well are hand-augured boring, auger drilling, mud-rotary drilling, air-rotary drilling, and cable-tool percussion drilling [29]. Of these methods, hand-augured boring is the least expensive. However, it is best suited for shallow borings (less than 4 m deep) that are only 5 to 15 cm in diameter. Auger drilling is suitable for depths of about 45 to 50 m.

P1.2. Collection and analytical methods

With the use of the installed and developed wells, it is possible to obtain samples that are chemically representative of the water taken in by the well. Consequently, attention must be directed to: 1) the physical extraction of the water from the well, 2) the preservation of the chemical integrity of the sample in transit to the place where it will be analysed, and 3) the attainment of analytical results that are accurate and have a high degree of precision.

Among the several means of collecting samples from the wells are: down-hole collection devices; suction-lift, positive displacement, gas-lift, and gas-drive methods; gas squeeze or bladder pumps; and jet or venturi pumps [31].

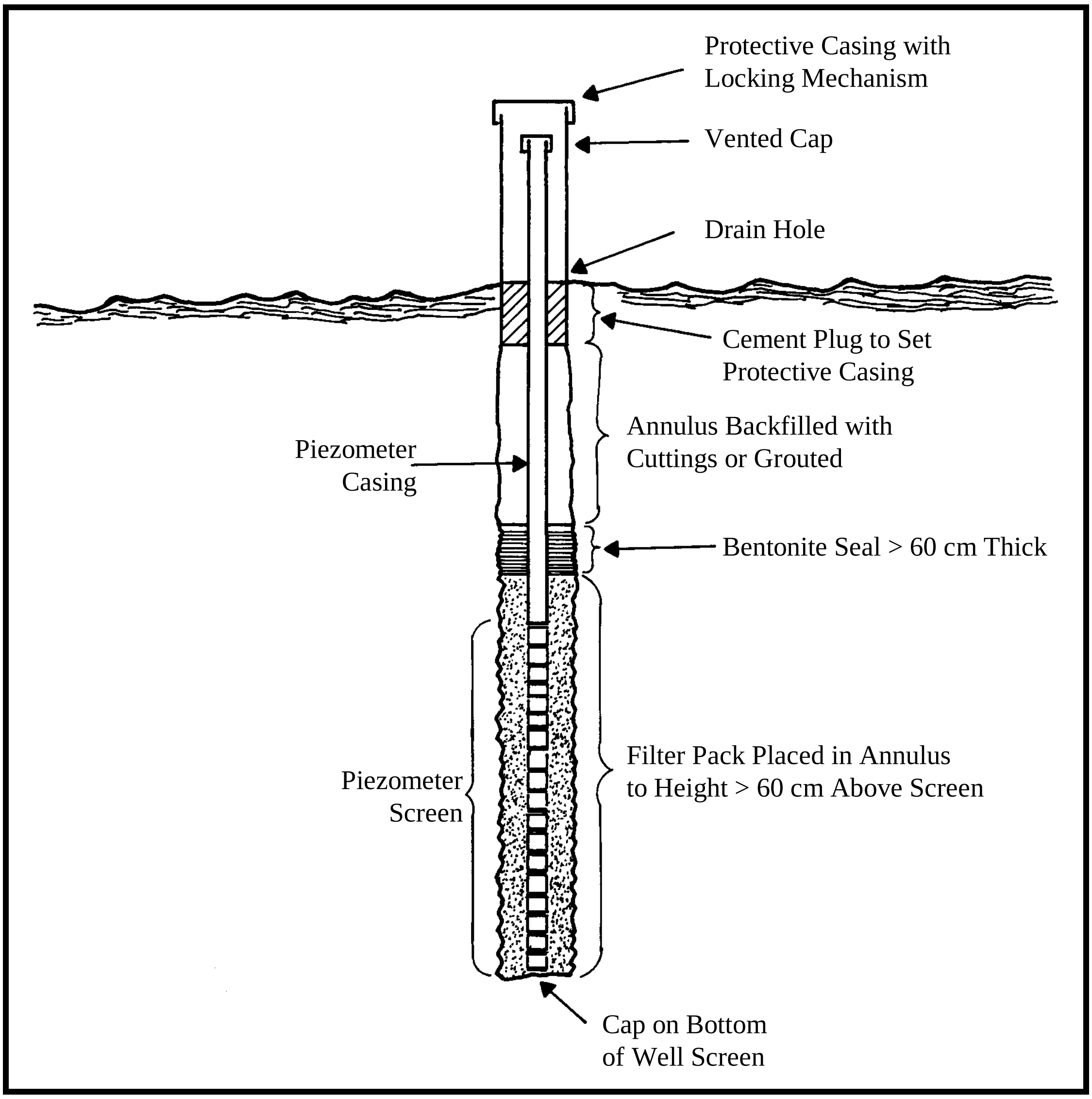


Figure XIV-27. Groundwater monitoring well

The following water quality parameters are recommended for analytical determination and monitoring due to the fact that the presence of them is a potential indicator of contamination by landfill leachate:

- pH,
- specific conductance,
- alkalinity,
- biological oxygen demand,
- chemical oxygen demand,
- nitrate/nitrite nitrogen,
- total (Kjeldahl) nitrogen,
- chloride,

- iron,
- sodium,
- manganesedium, and
- sulphate.

The pH level and specific conductance should be determined in the field, while the other sample analyses can be carried out by laboratories at universities or those that typically analyse the characteristics of potable water. The recommended frequency of sample collection and analysis is at least twice per year.

In addition to the water quality parameters listed above, analyses and monitoring for other metals and some organic chemicals should be considered for the groundwater testing program depending on the availability of financial resources and analytical testing capability. The additional list of parameters are listed below:

- arsenic,
- barium,
- cadmium,
- chromium,
- mercury,
- lead,
- selenium,
- total phenols, and
- volatile organic compounds.

These parameters can be monitored less frequently than twice per year and depending on site-specific conditions.

P2. SURFACE water

The necessity or advisability of monitoring surface water quality depends upon: 1) the proximity of the landfill to surface water, and 2) the drainage patterns between the fill and the surface water. The approach followed in the selection of sampling stations, equipment, and procedures should be similar to the approach used in the selection process for groundwater monitoring. The stations should be located in areas that have the greatest potential for contamination. These areas include the pathways through which leachate can enter a surface body of water. Flow patterns and seasonal variations should also be taken into consideration. Equipment used for sampling surface water and the methods used to analyse the samples should be consistent with procedures selected for testing groundwater samples.

P3. LANDFILL gas and migration

As stated in another section, landfill gas can escape by vertical and lateral migration. Obviously, if the landfill cover is sufficiently permeable, gas can exit vertically, i.e., through the cover. If the cover is impermeable (e.g., rain-saturated cover soil, pavement, or a clay or synthetic membrane cap) this escape route is blocked. Because of this blockage, lateral migration becomes the only avenue of escape. The distances involved in lateral migration can be significant, especially if the fill is adjacent to permeable soil strata.

Sampling devices should be located near the property boundary and offsite on the landfill side of structures in pathways most susceptible to gas migration. Simple gas probes can serve as gas sampling devices. The technique used in the collection of the samples is determined by the type of sampling probe. Methane usually is monitored by means of a portable meter. Methane gas concentration in facility structures, and in structures not on the facility, should not exceed 25% of the lower explosive limit. (The lower explosive limit is 5% methane.) In light of the mobility of landfill gas, precautions must be taken before human entry into any underground or confined space in the vicinity of a landfill. The space should be monitored for the presence and concentration of methane. Entry should be forbidden if the concentration is greater than 10% of the lower explosive limit.

Q. Uses of completed landfills

A completed sanitary landfill represents an opportunity to recover resources (landfill gas) or to construct facilities. Recovery of landfill gas is described in another section. The construction of several types of facilities on a landfill after its active life is described in the next several subsections. Because of the explosion hazard that results from the accumulation of landfill gas in enclosed spaces, housing and commercial construction on landfills should be limited to completely stabilised landfills unless special methods are used and precautions are taken.

Because of the many and often substantial constraints and limitations associated with the construction and utilisation of structures erected on a completed fill, the use of completed landfills as sites for construction and particularly for urban development generally is discouraged in industrialised countries [35]. However, in some locations a shortage of land prompts consideration of the potential of such sites. The situation is different in developing countries, especially in those in which the migration of populations from rural areas to the urban centres is substantial. Because of the migration, all unoccupied land has become attractive. Such being the case, the only recourse is to apply, to the fullest possible extent, precautionary measures designed to lessen associated hazards. Examples of proposed uses of completed fills are described in two World Bank reports: *Swamp Reclamation in Tropical Monsoon Regions by Appropriate Refuse Landfilling: Case Study Evaluations in Thailand* [36] and *Study of Landfill and Resource Recovery in Metropolitan Colombo* [37].

Constraints mainly take the form of problems associated with use of the site. Consequently, a sizeable share of these problems is geotechnical in origin and nature. Of equal importance is a group categorised as “potential hazards”.

Q1. GEOTECHNICAL problems

Settlement, a major geotechnical problem characteristic of all waste landfills, is addressed in another section. Not discussed in the previous section, however, is the problem posed by the relatively low bearing capacity of a completed fill. Despite variations in types of soil, in the characteristics of the landfilled wastes, and in the degree of settlement, the fact remains that reported values of bearing capacity indicate the prevalence of very low bearing capacities.

Reported values range from 2,440 to 2,910 kg/m^2. These rather low values apparently would restrict the construction of buildings on the completed fills to lightweight, single-story structures.

Q1.1. Solutions

The best course of action is to suspend the floor slab on sulphate-resistant cement piles. (The cement is of Class 4 or 5 (BRE 1981).) If the piles are made of materials other than concrete, they should be protected by corrosion-resistant material so as to cope with corrosive decomposition products in the fill.

A light, one-story building designed to accommodate settling may not require piling. However, its foundations should be reinforced to bridge gaps formed by differential settling. Continuous floor slabs reinforced as mats can also be used.

Roads, parking areas, and walkways should be constructed of flexible and easily repaired material.

Q2. POTENTIAL hazards

An important feature of the potential hazard of landfills is the fact that the potential persists as long as decomposition processes continue. Unfortunately, decomposition processes continue long after the site has been closed.

The three broad categories of potential hazards are landfill gas production, chemical contamination, and corrosion. In addition to the attention given here, gas production receives considerable attention in another section. Chemical contamination also is addressed elsewhere in this chapter.

Q2.1. Landfill gas production

As stated earlier, the rapid depletion of O_2 entrapped within the mass of buried wastes results in a rapid shift in the composition of the landfill gas from a preponderance of CO_2 to one of CH_4. The significance of this shift stems from the combustible and, under some conditions, explosive nature of CH_4. Because the rate of methane generation is extremely slow, methane production, *per se*, does not constitute a hazard. Consequently, methane becomes a combustible or explosive hazard only when the gas accumulates in a confined space within the fill itself or within a structure erected either on the fill or close to it. In some cases, pressure exerted by the buildup of landfill gases has been high enough to force the gas through permeable strata in soil adjacent to an unlined fill.

Although not necessarily hazardous, the malodorous nature of some trace constituents of landfill gas can be sufficiently intense as to constitute a problem. Examples of malodorous constituents are esters and organosulfurs. However, high dilution factors and low generation rates can sometimes, but not always, combine to keep malodorous gases from posing a problem in the use of the completed fill.

Q2.2. Corrosion

The hazard posed by corrosion is to building materials, utilities (pipes), and other items related to construction. The corrosion potential is in the many highly chemically active breakdown products found in decomposing municipal wastes. For instance, the mechanisms of attack on concrete include leaching of soluble materials, degradation of the binding capacities of cement by chemical change, disruption caused by expansion of reaction products, and crystallisation of salts within the concrete pores. With respect to utilities, metals are subject to attack by the acids generated within the fill as products of anaerobic decomposition. (Of course, steel reinforcement rods are subject to the same acid corrosion.)

Q2.3. Solutions

Procedures for preventing gas production from becoming a hazard at the fill and its environs are described in another section. Measures described in this section are specific to the use of the fill for construction and urban redevelopment. With regard to construction on a fill, the following measures should be taken:

- Install the floor slab carefully so as to prevent cracking and to keep the concrete from becoming porous.
- Do not allow cavities to develop under the slab.
- Install an impermeable plastic membrane within or beneath the floor slab.
- Lay the slab on a layer of gravel or crushed stone. The layer may be actively or passively ventilated.
- Build the structure above the surface of the landfill and incorporate a well ventilated subfloor area. Active ventilation involves the use of a pump capable of ensuring several air changes/hour. Passive ventilation (i.e., “naturally occurring”) is sufficient in situations in which the rate of gas evolution is low.
- Do not install utilities by penetrating the floor slab. Therefore, piping, conduits, etc. should enter the structure above floor-level.
- Install strategically located methane alarms in the structure.

Q3. RECOMMENDATIONS for construction on completed fills

The following recommendations are based on criteria reported in the literature [38]:

- Construction and urban redevelopment should not be allowed on a newly completed deep fill that has a large concentration either of industrial wastes or of freshly deposited highly organic wastes.
- The fill should have been completed ten years prior to redevelopment.
- The completed fill should not be deeper than 10 m.
- The fill site should have a stable, low water table.
- The fill itself should contain no toxic or hazardous wastes, particularly liquid wastes.
- The development should be in keeping with the site conditions.
- Expenditures on the development should be in keeping with the intended use of the development.

Redevelopment should not be approached solely on a cost-effective basis. The approach also must be equally satisfactory on an environmental basis. Thus, adequate safety measures must be taken into consideration in the design of structures.

Q4. POTENTIAL uses

As stated in the other sections, all uses of completed landfills are subject to certain constraints and limitations that remain in force until the biodegradable fraction of the buried wastes has been almost completely decomposed, and chemical and physical processes going on in the fill have reached a relatively high degree of stability, i.e., are approaching equilibrium. Among the more important of the constraints are those that arise from:

- the low bearing capacity of the fill cover,
- extensive settling (especially uneven settling),
- presence of combustible and explosive gases, and
- the corrosive character of decomposition products and the internal landfill environment in general.

These processes and their associated constraints continue long after the fill has been completed. The duration of this period is a function of climate (rainfall, temperature), nature of the buried wastes, and design and operational features of the landfill. For example, the duration may be as brief as two or three years in a developing country located in a humid, tropical setting and longer than ten years in an arid environment.

The uses may be divided into the three general categories: open space, agricultural, and urban developmental.

Q4.1. Open space and recreation

Although “recreation” and “open space” can be treated as separate land uses, they can also be regarded as mutually inclusive. Many reasons can be given for regarding recreation as being the most beneficial of the potential uses of a completed fill. In some cases, the completed fill probably provides the only site that will be available for recreation within the foreseeable future. The list of potential recreational uses is extensive. The types of uses largely reflect culture (e.g., cricket vs. baseball), although open space would appeal to the widest spectrum. It is important to note that all constraints attending the construction and use of structures apply to structures erected for recreational purposes.

Q4.2. Agriculture

The completed fill can be for agriculture when reservations concerning this use are taken into consideration. Among the agricultural uses are grazing, crop production, tree farms, orchards, nurseries, etc. In all cases, the final cover on the fill should be deep enough to ensure that roots do not come into contact with the buried wastes. Not only would such penetration be inhibitory to the crop plant(s), whether it be grass or trees, it may also serve as an avenue for introducing harmful substances into the food chain and the environment. The precaution becomes especially important when food crops are concerned. (Examples of root depths are: grasses - 0.7 m.; shrubs, corn, alfalfa - 1.3 m; trees with laterally branching root systems - 1.3 to 2 m; trees with tap root systems -- greater than 4 m.)

Q4.3. Construction and urban development

Even though construction and urban development are low priority uses, it is highly likely to occur in developing countries, especially in regions undergoing rapid or accelerated urbanisation. In these regions, vacant space for residential and commercial construction is becoming increasingly scarce. For example, in Cairo, apartment buildings for the poor are built on landfills. Every effort should be made to observe necessary constraints and precautions associated with this use.

Q5. REHABILITATION of existing facilities

In economically developing countries, the great majority of the land disposal sites are not equipped with bottom liners. Consequently, most of the land disposal sites do not have leachate collection and treatment systems. This situation may be acceptable in some arid- and semi-arid regions or in situations where the land disposal site is located remotely from sources of surface and groundwater. However, there are many communities located in areas that receive relatively large quantities of precipitation and, consequently, probably are polluting or will eventually pollute the soil and water resources.

A typical open dump in an economically developing country is operated without any fixed plans or procedures. Access to the site is not controlled, which inevitably leads to the presence of different types of animals feeding on the waste. Dumping on a down slope (e.g., at the top of a ravine or drop-off) is a typical practice. In such a case, no containment of the working face occurs, and the slope of waste is so steep that the waste is not compacted, nor is it likely in a state of structural stability.

The rehabilitation of an unmanaged land disposal site has several benefits associated with public health and the environment. In addition, the rehabilitation can be carried out in such a way that valuable space can be reclaimed. In some cases, additional landfill capacity can be achieved either through excavation and processing of the waste or through vertical expansion from the rehabilitated site.

There are a number of activities that should be carried out in any process of rehabilitation or closure of an existing dumpsite. The more important steps can be combined into the following: 1) preliminary study and evaluation, 2) performance of field work, 3) implementation of measures, 4) closure, and 5) beginning of sanitary landfilling operations (if applicable).

The preliminary study typically involves a thorough assessment of the current situation, location of wastes, verification of property lines, location of environmentally sensitive areas, distance to nearest dwelling, quality and type of access roads, general operating procedures, demand for additional capacity, and other factors. The procedures for either rehabilitating the site for future expansion or for closure are basically the same. The main difference between the two is the preparation of the surface to receive additional refuse.

Once the preliminary study has been completed and the main problems identified, the next step entails the performance of required field work. The field work may include perforation of wells, identification of groundwater and its quality, evaluation of migration of leachate and landfill gas, and other activities. The results of the tests should be analysed by professionals knowledgeable in the specific area (i.e., hydrology, geology, etc.). Based on the analyses, a series of recommendations can be formulated as a plan of rehabilitation.

In the event that leachate migration is identified as a problem, two routes of management can be followed. One is control of additional leachate generation and dispersal, and the second is preventing the migration of the leachate.

Control of leachate generation can be achieved through the control of run-on and run-off of precipitation and through the installation of an impermeable cover. Run-on to the landfill can be controlled by the construction of dikes, berms, or similar structures. Infiltration of the precipitation into the fill itself can be controlled by installing an impermeable layer at the proper inclination to promote runoff. The cover or cap will only prevent additional leachate from being generated. The thickness of the cap will depend upon the location as well as the intended use of the rehabilitated site. Settling and other processes should also be considered if the plan is to vertically expand the rehabilitated site.

In addition to the measures indicated in the preceding paragraphs, attention should be given to the management of the leachate already in the fill, as well as to the control of the landfill gas. Control of the leachate that will seep through the sides of the fill can be exercised through the installation of cut-off subsoil drains. The drains can be shallow or full depth. Shallow drains will, of course, be cheaper to install but may not solve the entire problem and only capture leachate seepage in the rainy season. Full depth cut-off drains designed to reach to the impermeable natural layer would prevent any seepage away from the site. Selection of the most appropriate alternative is a function of location, potential negative public health and environmental impacts, cost, and other factors. Finally, provisions must be made for the management of landfill gas, as well as the monitoring of the site [77].

If the contamination problems are very serious (e.g., contamination of an existing system of water supply), then more substantive actions may be indicated. These actions may involve excavation and removal of all the waste, and either repair of the facility for new landfilling or closure of the site and transport of the wastes to a sanitary landfill. Another alternative is the excavation and processing of the waste, reclaiming some of the recyclable materials, placing a liner or repairing the existing one, and discharging the residues in the repaired site. This process is known as landfill mining and reclamation (LFMR).

R. Economics

R1. BACKGROUND

The economic costs of individual disposal operations vary substantially from country to country and within each country. The variations are impacted by local conditions and regulations, as well as other factors not directly related to landfilling (e.g., assessments for funding recycling programs, etc.). The coverage discussed in this section is limited to the definition of the general components of landfill operation and their costs.

The cost of landfilling depends in part upon the type of waste disposed, size of the operation, availability of fill and cover material, and whether or not construction is phased. Phased landfill construction usually is cheaper than construction of the entire landfill site at one time. Varying site conditions and regulatory requirements for landfill construction are important factors in the variability among landfill construction costs.

As for accurately determining the landfill costs in a particular area, the best approach, when available, is to examine past and current landfill operations in that area. In each area, the cost of landfill disposal depends upon the cost of the land upon which the facility is developed, the design of the landfill, cost of labour, and governmental regulations that must be met.

Not only do landfill costs directly affect the total cost of waste management, they also have a bearing on the extent and nature of the processing to which the wastes might be subjected prior to ultimate disposal. In other words, the manner that wastes are managed by communities generating the wastes is determined to a considerable extent by the cost of disposing of those wastes. For example, if the cost of land disposal is low, waste reduction and recycling usually are given less emphasis than if the cost of disposal is high. Regardless of the level of economic development of a nation, landfill construction and operation costs usually are only a relatively small fraction of the total cost of waste management when and where the cost of property suitable for landfilling and the other development costs are low. Obviously, under such a circumstance, landfilling the wastes without pre-treatment usually would be the least expensive waste management alternative, although not necessarily the best option of managing the wastes. On the other hand, some form of waste processing to reduce amounts and volumes of wastes destined to be landfilled most likely would be economically justified in areas where land is expensive, scarce, or unsuitable for landfilling. Small, populated islands represent one example of meeting one or all of these land constraints

In most communities in developed countries, the cost of operating the landfill is recovered by means of a user fee. The fee typically is known as "tipping fee". Tipping fees generally vary as a function of weight, type of waste, and availability of landfill space.

R2. LANDFILL costs vs. total cost of solid waste disposal

The total cost of waste disposal is the sum of the costs for each component of the waste disposal operation. The disposal operation begins with the collection of waste from residential and industrial generators and ends with final management of the landfill site after closing (i.e., closure and post-closure). The total cost of each component of the waste disposal operation is the sum of its capital and operating costs.

The three leading operations are collection, hauling, and processing. Processing is optional. Collection involves the pickup of discarded materials from residential and industrial areas. Hauling is the transportation of the collected wastes either to the landfill or to central collection or processing locations. The actual burial of the wastes at a landfill constitutes landfill disposal. In developing nations, collection represents the major fraction of the costs for waste management.

R3. EFFECT of processing on cost of waste disposal

Baling is one method of processing wastes for the purpose of increasing the density of the collected waste, thereby reducing the volume of the waste to be disposed. This procedure increases the total capacity of the fill. Additionally, less cover soil is required. Expanding landfill capacity and easing cover soil requirements obviously lower landfill costs.

Removal of recyclable materials (e.g., scavenging, composting) is a form of waste processing that reduces the volume of waste destined to be landfilled. The recovery of recyclable materials may take place before, during, or after collection. Waste processing on a large scale, in order to recycle and reduce the quantity of waste landfilled, may be justifiable in areas where landfill capacity is low and alternate sites are remotely located (i.e., more than 50 km away).

One manner in which processing can reduce costs other than by volume reduction is by upgrading the quality of the waste to a level whereby exceptional landfilling measures are not required. Examples of exceptional measures have been described previously. Methods of upgrading the quality of wastes are: 1) detoxification of toxic wastes, 2) encapsulation or solidification of hazardous or toxic materials, and 3) removal of particularly objectionable types of putrescible wastes (i.e., market wastes).

R4. CAPITAL and operating costs

Among the principal capital costs are those of land, buildings and construction, and vehicles. These capital costs usually are fixed costs in that, as a rule, they are set during the course of the landfill operation. Labour required for operation and maintenance, fuel costs, and cost of cover material used during the operation of the landfill are all classified as operational costs. Operational costs are variable in that they generally are a function of the rate and magnitude of waste requiring disposal.

R5. LANDFILL cost models

A major difficulty in developing a landfill cost model that reflects conditions and costs in a developing country is the small amount and questionable reliability of available data. Such being the case, the logical approach is to estimate costs based on site specific data and other data that is relevant. This task can be considerably facilitated by following a suitable model for calculating the costs involved in sanitary landfilling. Such a guide or model has been proposed by L.E. Joyce [39] and is summarised in Table XIV-9. Variations of this model, including more complex ones with more variables, are commonly employed by waste managers in industrialised countries to estimate landfill costs.

Although the model is based on conditions and practices in the United States, it can be adapted for use in developing countries, because it is based on generic rather than specific principles. The costs given in the table can be considered as “indicators” of relative costs, and the distribution of costs among the cost elements is fairly typical of those of modern sanitary landfills in the United States. The elements of cost within each of the major cost categories listed in Table XIV-9 are described in detail in Table XIV-10. The cost elements listed in Table XIV-10 can serve as a checklist during the definition and preparation of costs for a landfill in any part of the world.

Table XIV-9. Model for estimating landfill costs and service fees (180 Mg/day facility) (US$)

COST BY MAJOR COST CATEGORY		
a.	Total pre-development	$887,000
b.	Total initial construction	$2,812,000
c.	Total annual operational	$1,323,000
d.	Annual closure/post-closure	$70,000
CALCULATION OF TOTAL ANNUAL COST		
e.	Capital costs (a + b)	$3,699,000
f.	Amortisation of capital costs (straight line depreciation over 20 years at 9%)	$401,000
g.	Annual operating cost (c)	$1,323,000
h.	Annualised closure and post-closure costs (d)	$70,000
i.	Total annual cost (f + g + h)	$1,794,000
CALCULATION OF UNIT COSTS AND SERVICE FEES		
j.	Annual Mg/year (180 Mg/day x 6 day/wk x 52 wk/yr)	56,200 Mg/yr
Unit cost (US$/Mg)		
k.	Cost/Mg (i ÷ j)	$32/Mg
l.	Host community fee for capital improvements	--
m.	State or local fee	--
n.	Total tipping fee (k + l + m)	$32/Mg
Cost/household/month		
o.	Annual cost (i)	$1,794,000
p.	Population	100,000 people
q.	Cost/person (o ÷ p)	$18/yr/person $1.50/month/person
r.	Persons/household	4
s.	Cost/household (q x r)	$6/month/household

Adapted from Reference 39.

The estimated costs listed in Table XIV-9 are those for a hypothetical 180 Mg/day modern sanitary landfill designed to serve a population of about 100,000 people in the United States. The facility is situated on a 100-ha site, of which 40 ha will be used for actual disposal of waste and 60 ha will serve as a buffer. The average excavation depth is about 3 m. The costs include a double lining system and a leachate collection and detection system. The facility is designed to operate 6 day/wk, 52 wk/yr [40,41]

Table XIV-10. Definitions of elements of cost within the major cost categories listed in Table XIV-9

Pre-Development Costs
Siting the facility (engineering, legal fees, and preliminary geotechnical investigations)
Site mapping (topographic/boundary surveys) and final geotechnical investigation
Engineering design and regulatory permit application
Legal and public hearings
Land purchase
Regulatory permitting fees
Administrative support services
Contingency
Initial Construction Costs
Entrance and access roads
General site excavation and land clearing
Erosion and sediment control facilities
Liners and liner cushion system
Leachate collection and landfill gas venting system
Leachate treatment system
Site landscaping
Scale system
Scalehouse and office building
Equipment maintenance facility
Public convenience area
Miscellaneous site paving
Miscellaneous (lighting, gates, signs, etc.)
Construction engineering and quality control testing
Annual Operational Costs
Site personnel and management
Facility overhead (e.g., building and site maintenance)
Equipment operations and maintenance
Fuel and electricity
Equipment rental
Road maintenance
Routine environmental monitoring (e.g., groundwater quality and landfill gas)
Engineering services
Site and equipment insurance/closure bonding
Ongoing development and construction costs
Leachate treatment at a municipal sewer system
Pre-treatment of leachate prior to disposal into municipal sewer system
Unanticipated costs
Closure and Post-Closure Costs
Engineering fees for preparation of a closure plan
Regulatory approvals of the closure plan
Final site grading and revegetation
Maintenance of erosion and sediment control facilities
Maintenance of landfill gas system
Operation and maintenance of leachate collection system
Leachate treatment

Additional estimated costs for landfilling are provided in Table XIV-11. The data in the table are presented for landfill sites having 100, 200, 300, and 400 ha in total area [40-43].

The estimated costs described in Tables XIV-9 and XIV-11 provide the reader with both a method to format cost estimates and a general understanding of the magnitude of costs for modern sanitary landfilling.

The Panamerican Center for Sanitary Engineering and Environmental Sciences (CEPIS), of the Panamerican Health Organization (PAHO), has developed a computer program to assist users in determining the costs of the various phases of waste management [34].

Table XIV-11. Examples of costs of sanitary landfilling, based on current conditions and practices in the United States (US$)

Item	Active Landfill Area			
	100 ha	200 ha	300 ha	400 ha
Pre-development[a]	430,000	520,000	610,000	700,000
Site preparation				
Clay (onsite)	8,700,000	18,300,000	29,500,000	42,200,000
Clay (16 km-haul)	10,600,000	21,800,000	34,600,000	49,300,000
Membrane/clay (onsite)	11,900,000	24,400,000	38,500,000	54,400,000
Membrane/clay (16-km haul)	12,900,000	26,400,000	41,700,000	58,600,000
Operations (per year)	220,000	380,000	530,000	580,000
Closure[b]	1,400,000 to 2,300,000	2,800,000 to 4,600,000	4,200,000 to 7,000,000	5,700,000 to 9,300,000
Post-closure[c] **(per year)**	170,000 to 340,000	240,000 to 480,000	350,000 to 700,000	460,000 to 920,000

[a] Items included in pre-development costs: environmental impact analysis/report, feasibility report, design and plan of operation, administration. Land costs are omitted.
[b] Items included in closure costs: earthwork, seeding, gas collection.
[c] Items included in post-closure costs: monitoring (groundwater, gas, leachate), leachate treatment, site maintenance, liability insurance, seeding, gas collection.

R6. LANDFILL equipment costs

Capital costs of heavy equipment used for landfilling refuse constitute a major cost component for the development of landfills. An indication of the magnitude of this component may be gained from the data presented in Table XIV-12. Because of the costs associated with sanitary landfilling, the acquisition of a sufficient number of the appropriate equipment for the efficient operation of a fill oftentimes is not carried out in developing countries.

Under U.S. conditions, the lifespan of mobile landfill equipment is generally estimated to be about 5 to 10 years.

In an industrialised nation, annual cost of maintaining heavy landfill equipment (lubrication, tire repair, parts, etc.) is estimated as being 15% to 20% of the original capital cost of the equipment. The actual cost in a developing country would depend very strongly upon the age of equipment, type of equipment, and maintenance procedures, as well as on the various factors peculiar to the country. However, the maintenance cost to capital cost ratios in the two settings probably would be similar.

As with maintenance costs, fuel costs vary with type and condition of the equipment. Obviously, they also depend upon the prices locally charged for the fuel. An indication of fuel consumption may be had from the data reported in References 44 and 89. According to those data, fuel consumption averages about 25 to 45 L fuel/hour.

Table XIV-12. Capital costs of some landfill equipment

Machine Type	Flywheel (kW)	Approx. Wt[a] (Mg)	Approx. Cost[b] (US$)	Comments
Tracked dozer	< 60	8 to 10	62,000 to 140,000	Standard/landfill blade
	67 to 97	12 to 16	88,000 to 205,000	Standard/landfill blade
	104 to 130	14 to 20	160, to 215,000	Standard blade
	186 to 209	26 to 34	385,000 to 485,000	Landfill blade
Tracked loader	< 68	9 to 11	75,000 to 100,000	GPB:[c] 0.8 m^3
	75 to 97	12 to 16	118,000 to 200,000	GPB: 1.5 m^3
	75 to 97	12 to 16	118,000 to 200,000	MPB:[d] 1.3 m^3
	119 to 142	16 to 22	260,000 to 415,000	GPB: 2.3 m^3
	119 to 142	20 to 24	260,000 to 415,000	MPB: 1.9 m^3
Rubber-tired loader	< 75	7 to 10	110,000	GPB: 1.3 m^3
	< 75	8 to 11	125,000	MPB: 1.1 m^3
	89 to 119	9 to 12	150,000 to 235,000	GPB: 3.0 m^3
	89 to 257	10 to 13	150,000 to 23312,000	MPB: 1.7 m^3
Landfill compactor	141 to 161	< 21	230,000 to 300,000	Landfill blade
	224 to 235	29 to 32	325,000 to 490,000	Landfill blade
	250 to 392	31 to 46	400,000 to 600,000	Landfill blade

Source: Reference 7 and CalRecovery, Inc.

[a] Basic machine plus engine sidescreens; radiator guards; reversible fan; roll bar; and either a landfill blade, general-purpose bucket, or multiple-purpose bucket as noted.

[b] 2002. The range of costs reflects differences regarding the equipment supplied by the manufacturer and regarding specifications of options supplied, and costs of taxes and import fees.

[c] General-purpose bucket.

[d] Multiple-purpose bucket.

S. Public participation

S1. INTRODUCTION

Because the environment has such an important bearing on the public's well being, and indiscriminate waste disposal is detrimental to environmental quality, the public usually demands an active role in waste management. Consequently, attention is being given to the adaptation and adoption of public involvement mechanisms and activities. Ideally, therefore, a public participation program should be established to actively involve citizens in all phases of developing waste management facilities, including site selection, design, operation, completion, and (in the case of landfills) use after closure.

Institutionally, many developing countries are not organised for active public involvement. Nevertheless, it is recommended that the public take part in the development of solid waste management facilities or, at the very least, be kept well informed of the plans. Uninformed groups can disrupt the development of waste management facilities, which can have serious adverse impacts on the overall waste management system.

S2. PRINCIPLES of public participation

An effective way of securing public participation in a landfill project is to secure public favour. Any existing opposition should be dissipated. On the other hand, the removal of opposition by itself is insufficient, since it would merely be replaced by the intermediate stage of indifference or disinterest. Although with regard to a landfill project, indifference or disinterest would mean no opposition, it would also mean no positive input for bringing the project to fruition. It is at this point that motivation and incentive come into play. They constitute the moving force needed for advancing public attitude to a favourable level.

Activities associated with public participation should be conducted under the leadership of a professional who has been trained in public relations and is well versed in conflict resolution.

S3. DISSIPATION of opposition

In this section, the public is divided into three groups, based on their position in the economic hierarchy and the relative influence they have on decision-making regarding public undertakings dealing with solid waste disposal. The three groups are: 1) financially distressed (poor), 2) middle income (intermediate), and 3) financially secure (wealthy).

For convenience of presentation in the discussion that follows, we refer to the first class as “poor”, the second class as “middle”, and the third class as “wealthy”.

S3.1. Poor class

The poor class is primarily concerned with basic survival. Consequently, any perceived threat to survival arouses opposition to the source of that threat.

For individuals whose principal source of income is scavenging, the development of a new landfill is a threat, and hence cause of opposition, if the landfill eliminates or curtails scavenging in any way other than to manage it. The obvious way to remove the threat is twofold:

1. Do not completely prohibit scavenging at the site. Manage it, confine it to a designated area, and impose regulations needed to ensure accident prevention and prevent interference with the efficient operation of the fill.

2. Assure the scavengers that, aside from the regulation needed to protect the safety of the workers and the public at large and to efficiently operate the fill, no steps will be taken to eliminate scavenging.

It may be difficult to dispel the suspicion almost universally held by the public regarding governmental regulations. Suspicion can be dispelled by showing the scavengers the plans and designs, and/or requesting input from their leaders. Word of that assurance can be spread by word-of-mouth; by way of scavenger associations, contractors, and others in the industry; by way of radio broadcasts, and public (official) announcements; and to some extent, by way of the printed media and "public education" programs.

Since a new site usually is located nearby to the waste generators, marginal lands for habitation by the poor can compete with the landfill. Regardless of the unsuitability of such low-grade land areas, they are the last recourse for living areas for some of the poor. Nevertheless, it may well happen that these populations have to compete for those sites with a landfill undertaking. It is not surprising that a strong opposition against any proposed landfill is aroused in those individuals.

Dispelling such a source of opposition can be a difficult task. An obvious way is to relocate the dispossessed individuals. Another approach to cope with the problem is to design and operate the landfill such that when completed, the site can provide living or recreational space, even though its promised remedy is postponed to a somewhat distant future. "Selling" that remedy to the affected individuals would be a difficult task, despite reliance upon the conventional means of making such an attempt. The best solution is to keep the number of those potentially affected to a minimum. Motivations in the form of sacrifices for the common good, preservation of the public health, patriotism, and similar approaches have little impact among a group for which mere survival is a pressing problem.

S3.2. Middle class

Middle class, as defined in an industrialised country, may either be non-existent or may be a relatively small group in a developing country. In this section, the term "middle class" is used for convenience and is intended to encompass a wide segment that neither fits within the poor class, nor is financially endowed to be categorised as wealthy. Therefore, this category includes individuals and professionals who are at the management and/or decision-making levels of the organisations for which they work. Examples of the organisations are small businesses and most branches of government. Also included in this category are some of the members of the educational system (principally primary and secondary schools), of the health care professions, informed concerned citizens groups, and others.

Reasons for landfill opposition are not as basic as those of the poor or as widespread. The concerns are not considered as basic because they do not concern survival. However, the important concerns relate to loss of living space and its quality-- space that already is extremely scarce. Most of the causes are in the form of perceived threats to: 1) health through contamination of resources and fostering the generation of insect and animal vectors, 2) quality of life, and 3) property values.

The opposition arising from concerns about health and quality of life could be considerable if not entirely eliminated by demonstrating that a properly designed and operated sanitary landfill would not be a threat. However, the fears regarding reduction of living space and lowering of property values would not be as easily allayed. The matter of the reduction of living space could be handled to some extent by way of the same measures prescribed for the poor. Addressing the adverse effects on value of surrounding property would be much more difficult. Of course, the difficulty would be considerably lessened if the proposed fill were to replace an open dump operation or by defining some type of compensation [54]. Compensation does not necessarily have to be financial. Compensation may also be in the form of the building of schools, parks, or community centres.

The best course of action is to publicise the advantages of a sanitary landfill. Because the greater percentage of the middle class is literate, "spreading the word" would be much easier than it would be among the poor class. The printed media, as well as radio and television, could also be put to use.

S3.3. Wealthy class

Opposition on the part of the wealthy probably would be neither as deep-seated nor as strong as among the other two classes. Moreover, chances of members of this class having any immediate contact with a fill usually would be remote. Any opposition would arise from a concern about deterioration of the quality of water resources in the area, endangerment of the health of the public at large (i.e., beyond the vicinity of the fill), or of lowering of the value of any nearby property that may be owned. Members of this class would dwell in the developed areas of the community in which the quality of the environment would approach that in an industrialised country. Because the cultural (social and attitudinal) characteristics would be comparable to those generally encountered in developed nations, measures taken to attract and engage their participation in a present or proposed sanitary landfill undertaking would also be comparable.

S4. OBJECTIVES of public participation

Although some of these objectives may be difficult to attain in many developing countries, they are included here to guide the more advanced developing countries and to serve as a model for those less developed. Among the objectives of a public participation program for this group and, to some extent, for the middle or intermediate group would be the following:

- The public should have the opportunity to understand official programs and proposed actions, and that the government gives due consideration to the public’s concerns.
- Official decisions on important activities should be made in concert with interested and affected segments of the public.
- The public must have every opportunity to participate in the decision-making process. In addition, the public’s participation must be stimulated and supported.

All of the objectives presented in the previous list can be accomplished by maintaining open communication between the landfill planners, designers and operators, and the public.

S5. ADVANTAGES associated with public participation

In addition to the advantages mentioned earlier, a well designed public participation program includes the following benefits: 1) provision of useful information to decision-makers; 2) assurance that all issues are fully and carefully considered; and 3) consideration by decision-makers of issues beyond the project, but which nevertheless have an influence on it.

As would be expected, public participation has some disadvantages. Among them are: 1) added cost to the project due to poorly executed public involvement, and 2) potential delays in the project due to public opposition and involvement of additional parties.

None of the disadvantages listed above is sufficient to outweigh the many benefits associated with an effective public participation program. The benefits are such that they facilitate the establishment of an effective decision-making process essential to a publicly-accepted landfill.

S6. PARTICIPANTS

Among the potentially more useful participants would be groups and individuals likely to be directly affected by the landfill. They would be strongly motivated because they would have a personal stake in the success of the project. Other useful participants would be those who have demonstrated a serious interest in environmental affairs. In fact, their participation should be encouraged in the process.

Among the organisations and individuals that should participate in a landfill siting process are the following: 1) members of the public; 2) representatives of consumer, environmental, and minority associations; and 3) representatives of trade, industrial, agricultural, labour, and civic organisations.

Identifying and gaining the support of the public early in the landfill siting process is important to a timely and orderly siting process and can also benefit subsequent solid waste management activities. Participation of all or most of the relevant individuals and organisations can be instituted through a citizens' advisory board. A citizens' advisory board is a critical component of many siting strategies [51].

S7. EXTENT of public input in relation to stage of project development

Although useful at all stages in the development of a sanitary landfill undertaking, public input can be critical at certain stages. For example, the first stage, the planning process, is a critical stage. It is critical because it is the stage in which public input has the greatest potential for shaping the final plan. For that reason it also is the time when involvement should be greatest. As a result of this early input, the public plays a proactive (or constructive) rather than a reactive role in decision-making. Appropriate mechanisms for shaping and applying this input are public hearings, public meetings, and workshops.

The site selection and design stage is the succeeding critical stage [47]. Potential additional approaches of information conveyance in this stage are audio-visual presentations and establishment of task forces for recommending design procedures in areas of particular public concern. Formal public hearings are essential at this time.

A third critical stage is the construction and operation stage. Although usable public input is perforce limited in this stage, the input nevertheless is critical, in that it is a means of monitoring the quality of construction and operation.

S8. CONCLUSIONS

Problems associated with the siting of a landfill (or any other waste processing facility) come about because real costs faced by individuals living near the proposed site have been ignored in the site selection process. If the developers of the landfill ignore perception costs, the developers are inviting dissatisfaction with policies by elements of the affected population. Thus, the siting of the landfill more than likely will be opposed by the population bearing these costs [48].

Experience in the United States and other countries (both industrialised and developing) has shown that individual risk perceptions are altered any time a solid waste facility is sited. This situation may take place even though the siting may decrease the level of potential adverse consequences for the population at large. One possible solution to this situation is the use of host-community benefits (HCBs). Host-community benefits are a well proven technique in siting various types of facilities considered undesirable by the public at large (i.e., large-scale electric generation plants, prisons, and others). The HCBs range from actual financial remuneration (host fees, tipping fees) to construction of parks, roads, schools, and other facilities that benefit the entire community. The application of HCBs, in essence, internalises the costs on those impacted by the decision [48,52,53].

In addition, if the economic benefit to the community is sufficiently large and the perceived degree of risk associated with the project is low, not-in-my-backyard (NIMBY) opposition is likely to be weak [49]. Compensation, however, should be complemented with non-monetary incentives such as monitoring and shared control [50,54].

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Part IV

Key Non-Technical Considerations