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Process Design Manual

Surface Disposal of Sewage Sludge and Domestic Septage

Contents

Chapter 1 Introduction

Chapter 2 Active Sewage Sludge Units

Chapter 3 Characteristics of Sludge, Septage, and Other Wastewater Solids

Contents (continued)

Page

Chapter 4 Site Selection

Contents (continued)

Page

Chapter 5 Public Participation Programs

Chapter 6 Field Investigations

Contents (continued)

Chapter 7 Design

Contents (continued)

Chapter 8 Surface Disposal of Domestic Septage

Chapter 9 Operation

Contents (continued)

Chapter 10 Monitoring

Chapter 11 Recordkeeping, Reporting, and Management for Surface Disposal

Contents (continued)

Chapter 12 Closure and Post-Closure Care

Contents (continued)

Page

Chapter 13 Costs of Surface Disposal of Sewage Sludge

Chapter 14 Design Examples

Contents (continued)

Page

Chapter 15 Case Studies

Chapter 1
Introduction

Human domestic activities generate wastewater that is piped into municipal sewer systems, underground septic tanks, or portable sanitation devices. Wastewater in municipal systems is treated before being discharged into the environment, as required under the Clean Water Act. This cleansing process generates a solid, semi-solid, or liquid residue—sewage sludge—which must be used or disposed (see Figure 1-1). Similarly, domestic septage—the solid, semi-solid, or liquid material that collects in septic tanks or portable sanitation devices that receive only domestic septage—must be periodically pumped out and used or disposed (see Figure 1-1).

Sewage sludge and domestic septage may be applied to the land as a soil conditioner and partial fertilizer, incinerated, or placed on land (surface disposal). Placement refers to the act of putting sewage sludge on an active sewage sludge unit[1] at high rates for final disposal rather than using the organic content in the sewage sludge to condition the soil or using the nutrients in the sewage sludge to fertilize crops. This manual provides practical guidance on the surface disposal approach to managing sewage sludge and domestic septage.[2] The manual:

- Describes the various types of active sewage sludge units.
- Provides guidance in selecting the most appropriate type of active sewage sludge unit for a particular situation.
- Details the engineering aspects of designing and operating a surface disposal site.
- Describes the applicable federal regulations.

The manual is intended for owners and operators of surface disposal sites, municipal officials involved in sewage sludge management, planners, design engineers, and regional, state, and local governments concerned with permitting and enforcement of federal sewage sludge management regulations.

1.1 Regulatory Overview

Most surface disposal of sewage sludge and domestic septage is subject to one of two sets of federal regulations, depending on whether the sewage sludge or domestic septage is disposed with or without household waste:

- Sites on which only sewage sludge, domestic septage, or a material derived from sewage sludge[3] are disposed, are regulated under Subpart C of 40 CFR Part 503.
- Codisposal of sewage sludge/domestic septage and household waste at a municipal solid waste (MSW) landfill[4] is regulated under 40 CFR Part 258.

This manual focuses on surface disposal sites subject to the 40 CFR Part 503 and on landfill units subject to Part 258 regulations. It explains the regulatory requirements for these sites or units and provides guidance on how these requirements influence selection, design, and operation of these sites or units. A complete discussion of the Part 258 regulations is beyond the scope of this manual. Instead, the Part 258 regulations are discussed specifically in regard to their impact on the codisposal of sewage sludge in municipal solid waste landfill units. For a more complete discussion of the Part 258 regulations the reader is referred to U.S. EPA, 1993.

Subpart C of Part 503 includes requirements for sewage sludge, including domestic septage, placed on a surface disposal site. Placing sewage sludge or domestic septage in a monofill, in a surface impoundment, on a waste pile, on a dedicated disposal site (DDS), or on a dedicated beneficial use site is considered surface disposal. A Part 503 standard for surface disposal of sewage sludge or domestic septage includes seven elements—general requirements, pollutant limits, management practices, operational standards, and requirements for the frequency of monitoring, recordkeeping, and reporting, as shown in Figure 1-2.

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[1] A sewage sludge unit is land on which only sewage sludge is placed for final disposal. An active sewage sludge unit is a sewage sludge unit that has not closed.

[2] U.S. EPA (1994), (1984a), (1984b), (1983), and (1979) provide guidance on land application and incineration.

[3] For example, a ***mixture*** of sewage sludge with nonhazardous solids (except for household waste), such as grit, screenings, commercial septage, and industrial sludge.

[4] Under Part 258, a municipal solid waste landfill is defined as a landfill that receives household waste and that may receive other nonhazardous waste.

guidance manuals for wetland delineation for regulatory purposes are the *Corps of Engineers Wetlands Delineation Manual* (COE, 1987) and the *Federal Manual for Identifying and Delineating Jurisdictional Wetlands* (Federal Interagency Committee for Wetland Delineation, 1989). The latter manual places greater emphasis on assessment of the functional value of wetlands, along the lines of earlier work by the U.S. Fish and Wildlife Service (USFWS, 1984).

Appendix C in U.S. EPA (1990c) provides summary information on more than 30 methods for assessment of wetland functions and values. Phillips (1990) describes a quantitative wetness index for use when field indicators of wetness are ambiguous or contradictory. Lyon (1993) may be useful as a supplemental reference for wetland identification and delineation. Finally, Mausbach (1994) provides a recent review of the historical development and current status of criteria developed by the SCS for classification of wetland soils, and notes that definitions are continuing to evolve as SCS develops and tests regional indicators of hydric soils.

6.4.5 Floodplain and Other Hydrologic Characterizations

As noted in Section 6.3.3, whether a site is located wholly or in part within a 100-year floodplain can be initially determined using a FEMA floodplain map or SCS soil survey. If there is any reason to suspect that actual sewage sludge disposal will occur on the floodplain, more detailed investigations will be required to accurately delineate the floodplain boundary. If disposal within the floodplain cannot be avoided, then the surface disposal site must be designed to include protective measures such as embankments or levies so that active sewage sludge units: (1) will not restrict the flow of the 100-year flood, (2) will not reduce the temporary water storage capacity of the floodplain, or (3) will not result in washout of pollutants that pose a hazard to human health and the environment.

Site-specific floodplain investigations may require analysis of meteorological and streamflow records; upstream topography, soils, and geology; aerial photograph interpretation; and assessment of existing and anticipated changes in watershed land use. The Interagency Advisory Committee on Water Data (Hydrology Subcommittee, 1982) provides guidelines for determining flood flow frequency using stream gauge records.

The U.S. Army Corps of Engineers (COE, 1982) has developed several numerical models to: aid in the prediction of flood hydrographs (HEC-1); create water surface profiles due to obstructions for evaluating flood encroachment potential (HEC-2); simulate flood control structures (HEC-5); and gauge river sediment transport (HEC-6). The HEC-2 model is not appropriate for simulation of sediment-laden braided stream systems or other intermittent/dry stream systems that are subject to flash-flood events. Standard runoff and peak flood hydrograph methods would be more appropriate for such conditions to predict the effects of severe flooding.

6.4.6 Geotechnical Characterization

Sewage sludge monofills and dedicated surface disposal sites that involve design of foundations, liners and leachate collections systems, and dikes/embankments will require detailed subsurface exploration, including sampling of subsurface solids and laboratory testing.

Subsurface exploration programs often use both indirect and direct methods, with direct methods required to confirm indirect observations. Indirect investigation methods include remote sensing techniques, such as aerial photograph interpretation (Section 6.3.1), and geophysical techniques, such as DC resistivity, electromagnetic induction, ground-penetrating radar, and seismic refraction. These methods do not require drilling or excavation. Selection of the proper geophysical techniques requires consideration of the purpose of the test, the character of the subsurface materials, depth limits of detection and resolution of possible methods, and susceptibility of methods to electrical or vibrational noise. While geophysical procedures can provide large amounts of data at a relatively low cost, they require careful interpretation that must be carried out by qualified experts only. Furthermore, geophysical data must be verified by direct procedures such as borings or test pits. Chapter 1 of U.S. EPA (1993c) provides additional information on remote sensing and surface geophysical methods.

Direct investigation methods include drilling boreholes and wells and excavating pits and trenches. Direct methods allow the site's geologic conditions to be examined and measured. Typically, boring logs should provide descriptions of the soil strata and rock formations encountered, as well as the depth at which they occur. In addition, the boring logs should provide standard penetration test results for soils and rock quality designation results for rock core runs. The boring logs also should record the intervals for, and the results of, any field hydraulic conductivity testing conducted in the borings.

Foundation soil stability assessments require field investigations to determine soil strength and other soil properties. In clayey materials, in situ field vane shear tests commonly are conducted in addition to collection of samples of subsurface material for laboratory testing of engineering properties. Soil samples can be obtained either by split spoon or thin-walled tube. Split spoon samples are disturbed and are of limited value other than for identification and assessment of water content. The thin-walled tube sample provides an undisturbed sample that can be used for a wide variety of laboratory tests.

Laboratory testing is conducted using representative soil samples. Testing, as appropriate, to evaluate the embankments, the foundation area, and areas under consideration as a source for borrow material covers: (1) ASTM/ Unified Soil Classification System (ASTM D2487-93, Test Method for Classification of Soils for Engineering Purposes), (2) grain-size distribution, (3) shrink/swell potential, (4) shear strength, (5) compressibility, (6) consolidation properties, (7) density and water content, (8) moisture-density relationships, (9) dispersivity, and (10) laboratory hydraulic conductivity. When evaluating foundation materials and liner materials, additional significant parameters for laboratory testing include cation exchange capacity and mineralogy.

The scope of the subsurface exploration program will vary depending on the complexity of the subsurface geology, seasonal variability in site conditions, and the amount of site information available. Typically, the investigator should drill an adequate number of borings across the site to characterize the underlying deposits and bedrock conditions and to establish a reasonably accurate subsurface cross section. Depth of borings is highly dependent on site-specific conditions. Typically, however, the borings should extend below the anticipated site base grade or below the water table, whichever is deeper. A sufficient number of water table observation wells and piezometers should be installed to define both the horizontal and vertical ground-water flow directions (Section 6.4.3). When subsurface heterogeneities are encountered that could lead to seepage or loss in strength in the foundation, additional subsurface exploration is sometimes necessary to identify and determine the extent of these features.

U.S. EPA (1988a) provides more detailed guidance on types of geotechnical information and on field and laboratory methods required for design of surface disposal sites; U.S. EPA (1986a) provides more detailed guidance on design, construction, and evaluation of clay liners. The following major references provide more detailed information on subsurface exploration techniques for geotechnical investigations: Bureau of Reclamation (1989, 1990), Hanna (1985), Hathaway (1988), Hvorslev (1949), USACE (1984), and U.S. Naval Facilities Engineering Command (1982).

Identification of Unstable Areas

U.S. EPA (1993d) classifies unstable areas that might restrict suitability for solid waste disposal as natural and manmade. Naturally unstable areas include:

- *Expansive soils*, which have a large percentage of clays with a high shrink-swell potential (smectite/montmorillonite groups, vermiculites, bentonite) or with sulfate or sulfide minerals present in the soil, make poor foundations. Such soils are readily identified by a soil survey. For example, any soils classified as vertisols (which have a high shrink-swell potential) would probably be unsuitable at a surface disposal site. Expansive soils tend to be found in the arid western states.
- Soils subject to *rapid settlement* (subsidence) also make poor foundations. Such soils include thick loess, unconsolidated clays, and wetland soils. Loess, found in the north central states, tends to compact when it is wetted. Unconsolidated clays and wetlands, on the other hand, subside when water is withdrawn.
- Areas subject to *mass movement* have rock or soil conditions that are conducive to downslope movement of soil, rock, and/or debris (either alone or mixed with water) under the influence of gravity. Examples of mass movement include landslides, debris slides and flows, and rock slides. These tend to occur most commonly on steep slopes, but sometimes conditions on gradual slopes favor mass movement.
- *Karst terrains* develop where soluble bedrock (typically limestone, but dolomite, and gypsum also might be subject to such effects) forms a subterranean drainage system where flow is concentrated in conduits. These areas tend to be characterized by caverns and sinkholes and subject to unpredictable, catastrophic rock collapse. The presence of sinkholes and soluble bedrock at or near the surface are a clear indication of site unsuitability. The absence of obvious karst geomorphic features (i.e., sinkholes) where limestone or other soluble bedrock is near the surface is not sufficient to determine stability. Fracture trace analysis using aerial photographs is an especially useful method for characterizing karst terrain (Section 6.3.1). Additional investigations, perhaps using surface geophysical techniques also might be required if no alternatives to siting in a karst area are available.

Examples of human-induced unstable areas include:

- The creation of cut and/or fill slopes during construction of the sewage sludge surface disposal site can cause slippage of existing soil or rock. At most sites the amount of earth-moving conducted is likely to be small enough that this will not be a major concern.
- Excessive drawdown of ground water can cause excessive settlement or bearing capacity failure of foundation soils. Again, this will not be an issue at most sewage sludge surface disposal sites; however, if a liner and a leachate collection system are to be used, system design should take this effect into consideration.

Another type of naturally unstable area includes *dispersive* soils where sodium-rich clays (which often also have a high shrink-swell) tend to disperse when wetted, allowing a form of subsurface erosion called *piping.* If any of the above conditions exist at a site and alternative sites with fewer problems are not available, more detailed geotechnical field investigations will likely be required. U.S. EPA (1993d) provides more detailed guidance on the approach that should be taken to assess site stability and design approaches for designing for stable slopes. U.S. EPA (1987 and 1988a) identify specific data needs and field and laboratory methods for geotechnical evaluation and design of different types of engineered structures.

6.5 Data Analysis and Interpretation

Analysis and interpretation of data from site-specific investigations for a dedicated sewage sludge disposal site focus on the following:

- Identification of areas of shallow ground water and assessment of the ground-water flow patterns at the site (Section 6.5.1).
- Provision of data required for establishing routine pollution control measures at the site, mainly surface runoff controls (Section 6.5.2).
- Documentation of the presence or absence of special site conditions that might impose special regulatory restrictions (Section 6.5.3) and, if present, presentation of data that show the limitations can be overcome by one or more engineering design approach (Section 6.5.4).

Computer modeling (Section 6.5.5) can facilitate all of the types of analysis listed above.

6.5.1 Identifying Areas of Shallow Ground Water and Ground-Water Flow Net Analysis

The investigations described in Section 6.4.3 should allow development of a relatively detailed water table contour map, which in combination with the site topographic map will facilitate development of an unsaturated zone thickness isopach map. Such a map can be used in several ways, including: (1) to identify areas of shallow ground water where it may be desirable to place some fill to increase the depth of saturation in the surface disposal site, or (2) to assess the relative attenuation capacity of the vadose zone within the surface disposal site.

Ground-water flow net analysis is a relatively simple graphical technique for gaining an understanding of ground-water flow patterns using water-table surface contour maps and three-dimensional hydraulic head data collected using procedures described in Section 6.4.4. As a first approximation, the general direction of ground-water flow at a site can be determined by drawing flow lines perpendicular to the water table contours. As illustrated in Figure 6-5, apparent directions of flow may change with depth. Flow lines drawn perpendicular to ground water equipotential contours should be considered only a first approximation because anisotropy in the aquifer (e.g., sites where horizontal hydraulic conductivity exceeds vertical hydraulic conductivity) will cause flow lines to diverge from the perpendicular. Figure 6-9 illustrates such a divergence in a fractured rock aquifer where vertical hydraulic conductivity is five times the horizontal hydraulic conductivity.

In ground-water recharge areas (i.e., hydraulic head decreases with increasing depth), it is important to recognize that pollutants entering the ground water will tend to move downward in the aquifer as well as laterally. Figure 6-10 illustrates this effect and shows how flow net analysis can be used to estimate pathlines where layered aquifer materials have different hydraulic conductivities. In this figure, a cross section of the aquifer has been drawn using the borehole logs from three, multilevel piezometer installations, and equipotential lines drawn using hydraulic head measurements at four or five levels in each piezometer. The angle of refraction of flow or equipotential lines is determined from the ratio of the hydraulic conductivities, which equals the ratio of the tangents of the angles formed by the flow lines. Figure 6-10 illustrates that the downward component of pollutant transport increases as hydraulic conductivity decreases. A significant implication of this effect is that downgradient ground-water monitoring wells that are screened in the upper portion of an aquifer may miss a pollutant plume in a recharge area, unless the aquifer has very high hydraulic conductivity.

Flow net construction and analysis requires knowledge of the hydraulic conductivity of aquifer materials. Hydraulic conductivity values also are required to estimate how rapidly pollutants might move if they enter the ground-water system. References in Table 6-7 should be consulted for guidance on the selection of aquifer test methods if field measurement of aquifer properties is required.

This section emphasizes flow net analysis because it provides a maximum amount of information about the hydrogeologic system at relatively low cost if procedures for collecting three-dimensional hydraulic head measurements described in Section 6.4.4 are used. Flow nets can readily be constructed manually, although use of computers for contouring data and graphic analysis can facilitate the process. Cedergren (1989), U.S. EPA (1986b) and Sara (1994) are recommended for more detailed guidance on construction and interpretation of flow nets. Flow net construction in anisotropic aquifers requires special procedures, which are covered in these references. Use of flow nets for placement of ground-water monitoring wells is discussed in Chapter 10.

6.5.2 Other Geotechnical Considerations

As noted in Section 6.4.6, some sewage sludge surface disposal sites will not require extensive geotechnical

Table 7-1. Sewage Sludge Surface Disposal Site Design Checklist (continued)

Step	Task
5	Prepare design package (continued)
	• Compute sludge storage volume, soil requirement volumes, and site life
	• Develop final location plan showing:
	- Normal fill areas and disposal areas
	- Special working areas
	- Leachate controls
	- Gas controls
	- Surface water controls
	- Access roads
	- Structures
	- Utilities
	- Fencing
	- Lighting
	- Washracks
	- Monitoring wells
	- Landscaping
	• Prepare elevation plans for monofills and surface impoundments with cross sections of:
	- Excavated fill
	- Completed fill
	- Phased development of fill at interim points
	• Prepare construction details
	- Leachate controls
	- Gas controls
	- Surface water controls
	- Access roads
	- Structures
	- Monitoring wells
	• Prepare cost estimate
	• Prepare design report
	• Submit application and obtain required permits
	• Prepare operator's manual

7.5 Design for Monofills, Surface Impoundments, and Piles and Mounds

7.5.1 Foundation Design

The following discussion is geared primarily toward active sewage sludge units that are lined and have leachate collection systems; however, good engineering practice requires that proper subsoil foundation design of all surface disposal sites be adequately addressed during the design phase.

Proper subsoil foundation design of an active sewage sludge unit with a liner is critical because liner system components, especially leachate collection pipes and sumps, can be easily damaged by stresses caused by foundation movement.

Good engineering guidance requires that foundations must be capable of providing support to the liner as well as resistance of pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression, or uplift.

Foundations for monofills or surface impoundments and lagoons should provide structurally stable subgrades for the overlying components. The foundations also should provide satisfactory contact with the overlying liner or other system components. In addition, the foundation should resist settlement, compression, and uplift resulting from internal or external pressures, thereby preventing distortion or rupture of overlying components (U.S. EPA, 1988a).

7.5.1.1 Field Investigation

Adequate field investigations are necessary to ensure that the foundation design is developed to accommodate expected site conditions. Field investigations are designed to establish the in situ subsurface properties, site hydrogeologic characteristics, and the area seismic potential, all of which are critical to the design of a surface disposal site. Subsurface exploration programs are conducted to determine a site's in situ subsurface properties, as well as its geology and hydrogeology. The in situ subsurface properties and hydrogeologic characteristics have a significant influence on the bearing capacity, settlement potential, slope stability, and uplift potential for the site. The site's subsurface geology may impact the settlement and seismic potential at the site and exert an influence on the site's hydrogeology characteristics. See Chapter 6 for a more extensive discussion on field investigations and subsurface explorations programs.

7.5.1.2 Foundation Description

Foundation design procedures are site specific and very often are an iterative procedure. A typical preliminary foundation description should include (U.S. EPA, 1988a):

- Geographic setting
- Geologic setting
- Ground-water conditions
- Soil and rock properties
- Surface-water drainage conditions
- Seismic conditions
- Basis of information

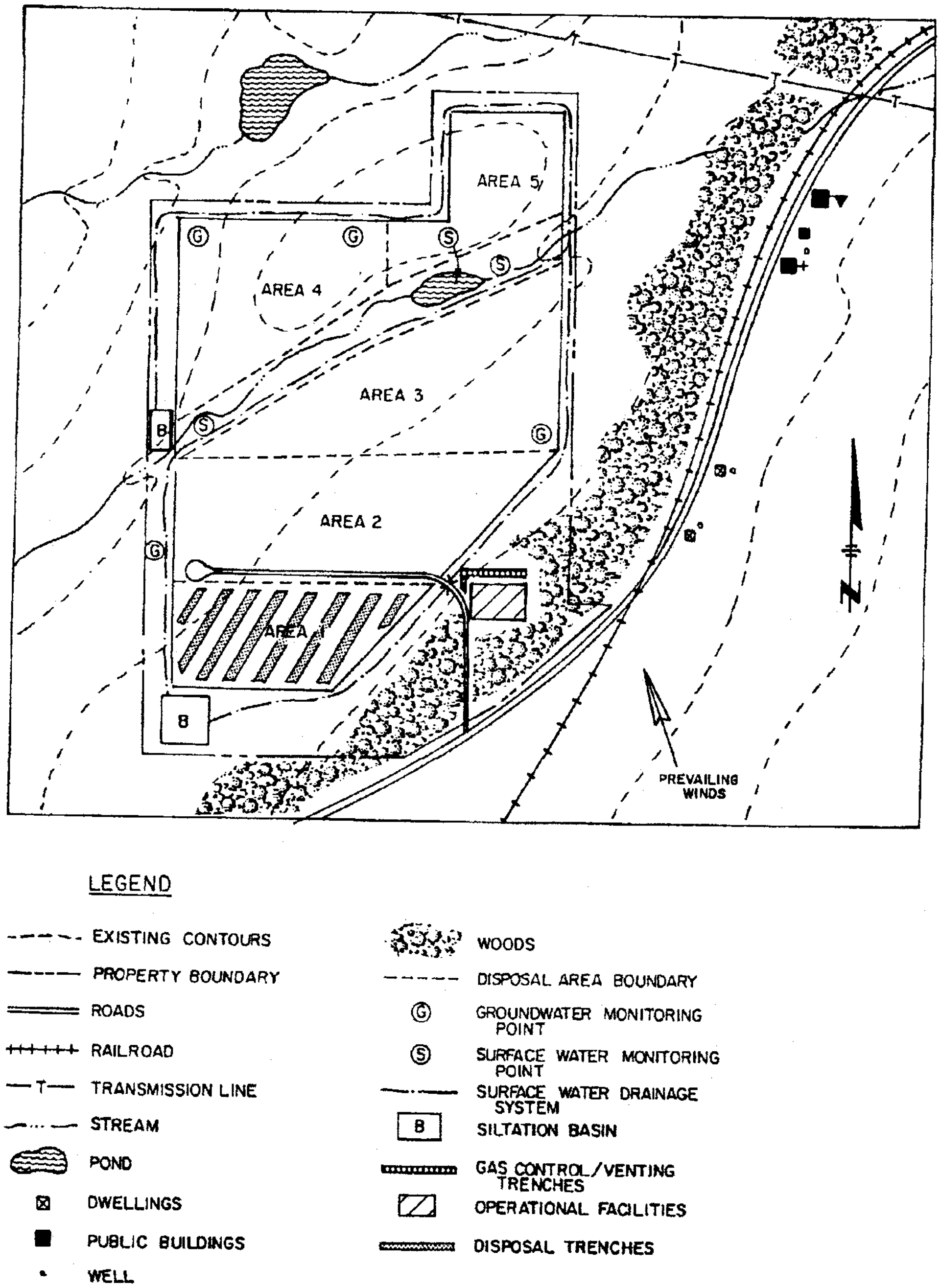


Figure 7-2. Typical site plan.

Site plans should include the active sewage sludge unit locations within the site; the unit depths, configurations, and dimensions; and whether the unit will be completed below or above grade. It is particularly important that the investigation borings, test pits, and other procedures described in Chapter 6 be performed as near as possible to the active sewage sludge units, if not within their boundaries. Some other critical elements of the foundation design that need to be addressed prior to completion of the field investigation are the foundation design alternatives, the foundation grade, the loads exerted by the unit or the foundation, and the preliminary settlement tolerances.

7.5.1.3 Foundation Design

The engineering analysis for foundations is based on subsurface conditions; however, the results of such analyses are based on loading conditions. To perform the appropriate engineering analysis to demonstrate the adequacy of the foundation, an accurate estimate of the loadings should be prepared, in addition to plans showing the structure's shape and size, the expected waste characteristics and volumes, and the foundation elevations.

Foundations are designed to (U.S. EPA, 1988a):

- Provide structural support and to control settlement
- Prevent bearing capacity failure
- Withstand hydrostatic pressures

These are all discussed below.

Settlement and Compression

The foundation should be capable of preventing failure of the liner system due to settlement and compression. Therefore, it is important that an analysis be carried out estimating total and differential settlement/compression expected due to the maximum design loadings. The results of this analysis are then used to evaluate the ability of the liner system as well as the leachate collection and recovery systems to maintain their integrity under the expected stresses (U.S. EPA, 1988a).

A settlement analysis will provide an estimate of maximum settlement. This maximum settlement can be used to aid in estimating the differential settlement and distortion of an active sewage sludge unit. Allowable settlement is typically expressed as a function of total settlement, rather than differential settlement, because the latter is much more difficult to predict; however, the differential settlement is a more serious threat to the integrity of the structure than total settlement (Lambe and Whitman, 1969; Wahls, 1981).

Active sewage sludge unit design calculations should include estimates of the expected settlement, even if it is expected to be small. Small amounts of settlement, even a few inches, can cause serious damage to leachate collection piping or sumps.

Bearing Capacity

For active sewage sludge units, the major issue of concern for foundations is differential settlement; however, for structures such as leachate risers, an additional area of concern is bearing capacity failure (U.S. EPA, 1987a).

The basic criterion for foundation design is that settlement must not exceed some permissible value. This value varies, dependent on the structure and the tolerance for movement without disruption of the unit's integrity. To ensure that the basic criterion is met, the bearing capacity of a soil, often termed its stability, is the ability of the soil to carry a load without failure within the soil mass. The load carrying capacity of soil varies not only with its strength, but often with the magnitude and distribution of the load. The reference Sowers and Sowers (1970) provides information regarding the evaluation of bearing capacities and typical ranges of key parameters. After the bearing capacity is determined, the settlement under the expected load conditions should be estimated and compared to the permissible value. The foundation design should be such that the actual bearing stress is less than the bearing capacity by an appropriate factor of safety (U.S. EPA, 1987a; Winterkorn and Fang, 1975; Lambe and Whitman, 1969).

Seepage and Hydrostatic Pressures

Foundations should be designed to control seepage and hydrostatic pressures. Heterogeneities such as large cracks, sand lenses, or sand seams in the foundation soil offer pathways for leachate migration in the event of a release through the liner and could cause piping failures. In addition, soft spots in the foundation soils due to seepage can cause differential settlement possibly causing cracks in the liner above and damaging any leachate collection or detection system installed. Cracks also can be caused by hydrostatic pressure where the latter exceeds the confining pressure of the foundation and liner (U.S. EPA, 1986b).

Solutions to these problems include various systems that are available to lower the hydraulic head at the active sewage sludge unit. These systems include pumping wells, slurry walls, and trenching. Other methods to control foundation seepage include grouting cracks and fissures in the foundation soil with bentonite and designing compacted clay cut-off seals to be emplaced in areas of the foundation where lenses or seams of permeable soil occur (U.S. EPA, 1986b).

7.5.2 Monofill Design

Several monofills were identified and described in Chapter 2, Surface Disposal Practices. These include:

- Sludge-only trench
  - Narrow trench
  - Wide trench
- Sludge-only area fill
  - Area fill mound
  - Area fill layer
  - Diked containment

Chapter 2 provides a detailed discussion on each of these monofills, and Table 2-1 lists the most significant features affecting monofill selection, which are:

- Sludge percent solids.
- Sludge characteristics (stabilized or unstabilized).
- Hydrogeology (deep or shallow ground water and bedrock).
- Ground slopes.

  - Evaporation rate (annual average, range, and seasonal fluctuations).
  - Temperature extremes.

- *Subsoil Permeability.* The subsoil should have a moderate permeability of 1.6×10^{-4} to 5.5×10^{-4} in. per second (4.2×10^{-4} to 1.4×10^{-3} cm/s).
- *Sludge Characteristics.* The type of sludge to be placed in the lagoon can significantly affect the amount and type of odor and vector problems that can be produced. It is recommended that only anaerobically digested sludges be used in drying lagoons.
- *Lagoon Depth and Area.* The actual depth and area requirements for sludge drying lagoons depend on several factors such as precipitation, evaporation, type of sludge, volume and solids concentration. Solids loading criteria have been given as 2.2 to 2.4 lb of solids per year per cu ft (36 to 39 kg/m^3) of capacity. A minimum of two separate lagoons are provided to ensure availability of storage space during cleaning, maintenance, or emergency conditions.
- *General Guidance.* Lagoons may be of any shape, but a rectangular shape facilitates rapid sludge removal. Lagoon dikes should have a slope of 1:3, vertical to horizontal, and should be of a shape and size to facilitate maintenance, mowing, passage of maintenance vehicles atop the dike, and access for the entry of trucks and front-end loaders into the lagoon. Surrounding areas should be graded to prevent surface water from entering the lagoon. Return must exist for removing the surface liquid and piping to the treatment plant. Provisions must also be made for limiting public access to the sludge lagoons.

Design criteria for drying lagoons are presented in Table 7-7; Table 7-8 lists advantages and disadvantages of sludge drying lagoons.

7.5.4 Design of Piles and Mounds

Piles and mounds are sites where dewatered sludge is placed on part of the POTW property as final disposal. In general, piles and mounds are suitable only for stabilized sludges with a high chemical content (greater than 40 percent lime plus some ferric) or a very low organic content (less than 50 percent solids), or for highly stabilized lagoon sludges. Piles of mechanically dewatered sludge with less than 25 percent solids usually lose all semblance of stability when exposed to extensive rainfall (U.S. EPA, 1979).

As surface disposal facilities, piles and mounds are subject to the requirements of the Part 503 rule (e.g., requirements for pathogen control, vector attraction reduction, pollutant limits, siting, restriction of public access, runoff collection, and ground-water protection). To protect ground water, it is recommended that piles and mounds be located on an impervious surface (U.S. EPA, 1990). Many states also have regulations regarding sludge stockpiles. Check with your state for any specific state requirements for sludge stockpiles.

7.5.5 Slope Stability and Dike Integrity

Certain types of monofills (area fills) and surface impoundments are constructed above natural grade through the use of earthen dikes, excavated below grade slopes constructed around the unit, or some combination of dikes and excavation, depending on site topography. These excavated slopes and earthen dikes are vulnerable to stability failures via several mechanisms. Slope and dike failures can seriously damage a liner system, allowing releases of leachate to surrounding soils and ground water.

For these reasons, earthen dikes must be carefully designed, and excavated slopes must be carefully evaluated to ensure that they are sufficiently stable to

Table 7-7. Design Criteria for Drying Lagoons (Lue-Hing et al., 1992)

	Design Parameter
a. Solids loading rate	
Primary sludge	96.1 kg/m^3/year
—(lagoon as a digester)	(6 lbs/ft^3/year)
Digested sludge	35-38 kg/m^3/year
—(lagoon for dewatering)	(2.2-2.4 lbs/ft^3/d)
b. Area required	
Primary sludge	0.0929 m^2/capita
(dry climate)	(1 ft^2/capita)
Activated sludge	0.31586 m^2/capita
(wet climate)	(3.4 ft^2/capita)
c. Dike height	60 cm (2 ft)
d. Sludge depth after decanting—depths of 60 cm to 1.2 m (2-4 ft) have been used in very warm climates	38 cm (15 in.)
e. Drying time for depth of 38 cm (15 in) or less	3 to 5 months

Table 7-8. Advantages and Disadvantages of Using Sludge Drying Lagoons (U.S. EPA, 1979)

Advantages	Disadvantages
Lagoons are low energy consumers	Lagoons may be a source of periodic odor problems, and these odors may be difficult to control
Lagoons consume no chemicals	There is a potential for pollution of groundwater or nearby surface water
Lagoons are not sensitive to sludge variability	Lagoons can create vector problems (for example, flies and mosquitos)
The lagoons can serve as a buffer in the sludge handling flow stream. Shock loadings due to treatment plant upsets can be discharged to the lagoons with minimal impact	Lagoons are more visible to the general public
Organic matter is further stabilized	Lagoons are more land-intensive than fully mechanical methods
Of all the dewatering systems available, lagoons require the least amount of operation attention and skill	Rational engineering design data are lacking to allow sound engineering economic analysis
If land is available, lagoons have a very low capital cost	

withstand the loading and hydraulic conditions to which they will be subjected during the unit's construction, operation, and post-closure periods. This section describes how to design and evaluate dikes and slopes for stability. For more information on slope stability and dike integrity at land disposal facilities, including information on materials specifications and embankment construction, the reader is referred to references U.S. EPA, 1988a, and U.S. EPA 1993a.

7.5.5.1 Slope Stability Failure

Slope stability failures occur when sliding forces from the weight of the soil mass itself and external forces including sludge pressures exceed the resisting forces from the strength of the soil and from any reinforcing structures. Slope stability analysis consists of a comparison of these resisting forces (or moments) to the sliding forces (or moments) to obtain a factor of safety (FS). Generally, the FS takes the following form (Sowers, 1979):

$$FS = \frac{\text{Sum of resisting moments}}{\text{Sum of sliding moments}}$$

When a stability analysis is performed, a slope is analyzed for one or more of several potential modes of failure. A safety factor is obtained for each mode, the lowest FS being the most critical.

Table 7-9 lists the EPA-recommended minimum factors of safety for slope stability analyses. If a dike or excavated slope design analysis yields lower safety factors, then steps should be taken to reduce the sliding forces or increase the resisting forces, or the slope should be redesigned to produce a safer structure.

Slope stability failures usually occur in one of three major modes, depending on the site soils, slope configuration, and hydraulic conditions (U.S. Dept. of the Navy, 1982). These three major failure modes are the following:

- Rotation on a curved slip surface approximated by a circular arc.
- Translation on a planar surface that is large compared to the depth below ground.
- Displacement of a wedge-shaped mass along one or more planes of weakness in the slope.

Figure 7-19 illustrates basic concepts of rotational and translational failures.

In addition to the three major failure modes, dikes and excavated slopes are also vulnerable to failure due to differential settlement, seismic effects including liquefaction, and seepage-induced piping failure. Safety factors are determined in a manner similar to those for the three major failure modes. These failure modes are discussed in greater detail below.

7.5.5.2 Stability Analyses

A stability analyses should consider (U.S. EPA, 1988a):

- The adequacy of the subsurface exploration program.
- The stability of the dike slopes and foundation soils.
- Liquefaction potential of the soils in the dike and the foundation.
- The expected behavior of the dike when subjected to seismic effects.
- Potential for seepage-induced piping failure.
- Differential settlements in the dike.

Subsurface Exploration Program

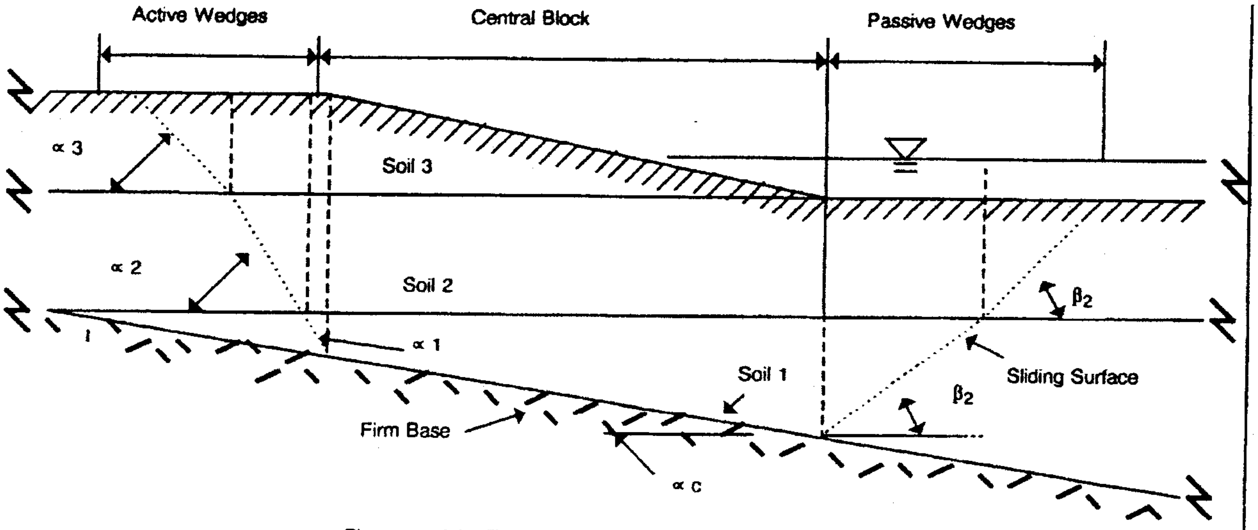
As discussed in Section 7.5.1, field investigations are necessary to evaluate the foundation for a constructed dike, to evaluate dike materials obtained from a borrow area, and to evaluate a slope excavated below ground. Of particular importance in some circumstances are laboratory strength tests performed on soil samples to

Table 7-9. Recommended Minimum Values of Factor of Safety for Slope Stability Analyses (U.S. EPA, 1988a)

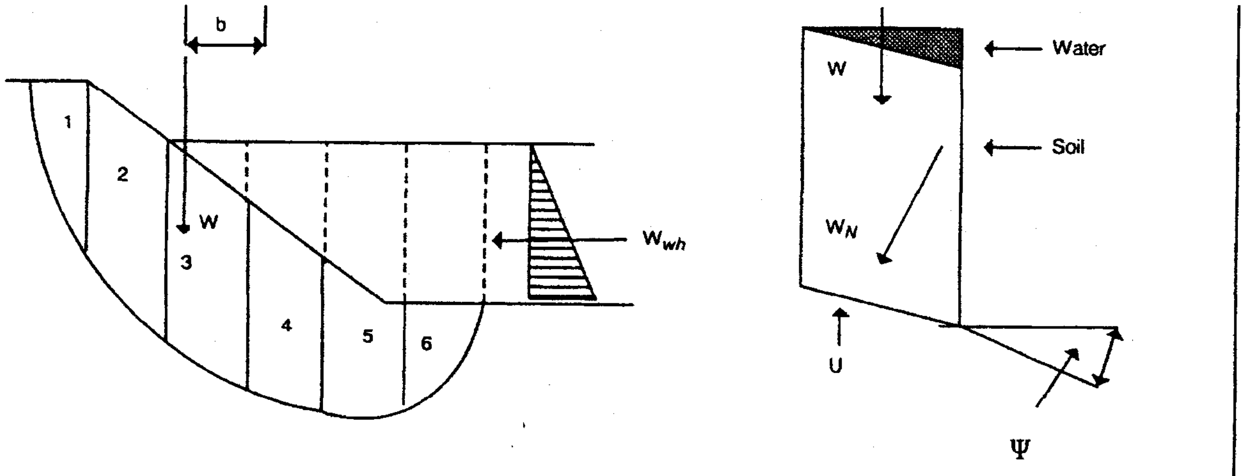
	Uncertainty of Strength Measurements	
Consequences of Slope Failure	Small$_1$	Large$_2$
No imminent danger to human life or major environmental impact if slope fails	1.25 (1.2)*	1.5 (1.3)
Imminent danger to human life or major environmental impact if slope fails	1.5 (1.3)	2.0 or greater (1.7 or greater)

1. The uncertainty of the strength measurements is smallest when the soil conditions are uniform and high quality strength test data provide a consistent, complete, and logical picture of the strength characteristics.
2. The uncertainty of the strength measurements is greatest when the soil conditions are complex and when available strength data do not provide a consistent, complete, or logical picture of the strength characteristics.

* Numbers without parentheses apply for static conditions and those within parentheses apply to seismic conditions.



Elements of the Translational (Wedge) Slope Stability Analysis
(Reference 4, p. 42)



a. Circular segment divided into slices

b. Forces acting on slice 3

Method of Slices for Circular Arc Analysis of Slopes in Soils Whose Strength Depends on Stress (Reference 3, p. 578)

Figure 7-19. Conceptual slope failure models (U,S. EPA, 1988a).

determine the strength of the foundation and embankment soils under the expected conditions of saturation and consolidation (see Chapter 6).

Field and laboratory data are used to obtain a detailed characterization of the site with respect to the engineering properties of the soils and rock. These engineering properties provide the input data for evaluation of the stability of slopes. Slope stability analysis requires the establishment of various site conditions including (U.S. EPA, 1988a):

- The soil shear strength conditions that represent actual site conditions.
- The steady-state hydraulic boundary conditions occurring through the site's section.
- The seismic conditions established for the site area.

For slope stability analyses, the most critical soil parameter is that of shear strength (U.S. EPA, 1988a). The shear strength of a soil is a measure of the amount of stress that is required to produce failure in plane of a cross section of the soil structure. The shear strength of a soil must be known before an earthen structure can be designed and built with assurance that the slopes will not fail (U.S. EPA, 1986b). To adequately determine a soil's shear strength, the potential effect of pore water pressures from the expected site loading conditions must be considered during testing.

While laboratory soil strength testing data is highly desirable, these tests are limited to small-size samples, and in many locations dikes are constructed using material that contains large particle sizes. Furthermore, in existing dikes, the type of material may make the obtaining of undisturbed soil samples nearly impossible. Therefore, it is not uncommon in standard engineering practice to estimate or assume these parameters based on the best data available. While it is acceptable to do this, it must be done and evaluated by a qualified geotechnical engineer (U.S. EPA, 1988a).

Slope stability also is dependent on hydraulic conditions in the slope. Potential hydrostatic or seepage forces from large hydraulic gradients should be identified and considered during the stability analyses. Ground-water levels and hydraulic analyses are used to determine the configuration of the steady-state piezometric surface through sections of the foundation and/or the dike structure. For sections involving a steep piezometric surface or an upstream static or flood pool, hydraulic analyses also determine seepage quantity, critical (highest) exit gradient, and potential for uplift of a clay liner due to excess pore pressures produced by a confined seepage condition (U.S. EPA, 1986b).

Hydraulic boundary conditions may reflect unconfirmed, steady-state seepage conditions, or confined seepage conditions involving an impermeable barrier (soil liner) and excess pore pressure on the barrier. The hydraulic conditions of a slope are determined using seepage analysis, as discussed by Freeze and Cherry (1979).

Slope Stability

Slope stability analyses are performed for both excavated side slopes and aboveground embankments. Three analyses will typically be performed as appropriate to verify the structural integrity of a cut slope or dike; they are (U.S. EPA, 1988a):

- Slope stability
- Settlement
- Liquefaction

Table 7-10 indicates the minimum required soil parameter data usually needed to perform these analyses.

The slope stability is typically evaluated using either a rotational (slip circle) analysis and/or a translational (sliding block or wedge) analysis using a computer model. These analyses are run for both static and dynamic (seismic) conditions. For large dikes in areas of major earthquakes, a more rigorous method of dynamic analysis may be warranted.

Analyses to establish total and differential settlement are also performed to ensure that the estimated settlement will not adversely affect the integrity of the unit and its components.

The liquefaction analysis determines the potential for liquefaction of the dike and foundation soils to occur during seismic events.

Rotational Slope Stability Analysis. A rotational slope stability analysis is typically performed using a method that divides the slope into discrete slices and sums all driving and resisting forces on each slice (see Figure 7-19). For each trial arc, the section is subdivided into vertical slices, each having its base coincident with a portion of the trial arc. Slices are defined according to the section geometry such that the base of each slice comprises only one soil type. The driving and resisting forces acting on each slice are then used to compute driving and resisting moments about the center of rotation of a circular section of the slope. The overturning and resisting moments for each slice are then summed and the FS is computed (U.S. EPA, 1986b).

Translational Slope Stability Analysis. The major features of the translational analysis are the same as those for the rotational case except that the trial surface consists of straight line segments that form the base of one or more active (thrusting) wedges, a neutral or thrusting central block, and one or more passive (restraining) wedges (see Figure 7-19). This analysis is based upon selection of a trial central block defined by the surface and subsurface soil layer geometry, followed by compu-

Table 7-10. Minimum Data Requirements for Stability Analysis Options (U.S. EPA, 1988a)

Soil Parameter	Units	Stability Analysis Options			
		Rotational	Translational	Settlement	Liquefaction
1. Cohesion* (UU, CU, CD cases)	pounds/sq.ft. (psf)	X	X		X CD
2. Angle of internal friction* (UU, CU, C cases)	degrees	X	X		
3. Total (wet) unit weight	pounds/cu. ft. (pcf)	X	X	X	X
4. Clay content	percent (0 to 100)				X
5. Overconsolidation ratio	unitless (decimal)			X	
6. Initial void ratio	unitless (decimal)			X	
7. Compression index	unitless (decimal)			X	
8. Recompression index	unitless (decimal)			X	
9. Hydraulic conductivity** (permeability, k)	ft/yr				
10. Median grain size	mm				X
11. Plasticity index (PI)	percent (0 to 100)				X
12. Liquid limit (LL)	percent (0 to 100)				X
13. Standard penetration number (N)	unitless (integer)				X

* Required strength case dependent upon hydraulic boundary condition selected

** Used only in hydraulic analysis

tation of the coordinates for the associated active and passive wedges (U.S. EPA, 1986c).

Settlement Analysis. Settlement analysis is used to determine the compression of foundation soils due to stresses caused by the weight of an overlying dike. Required parameters for each soil include unit weight, initial void ratio, compression and recompression indices, and the over-consolidation ratio (U.S. EPA, 1986c). Settlements are calculated at the toes, crest points, and centerline of the dike. The consolidation of each soil is calculated for each layer and summed up for all soils to determine the total settlement at each point. Differential settlements are calculated between each toe and crest, toe and centerline, and crest and centerline on both sides of the dike. Recommended maximum differential settlements can be found in EPA, 1986c.

Liquefaction Analysis. Factors that most influence liquefaction potential are soil type, relative density, initial confining pressure, and the intensity and duration of earthquake motion (U.S. EPA, 1986c). Methods for estimating the potential for liquefaction are provided in a computer software package called Geotechnical Analysis for Review of Dike Stability (GARDS) that has been developed by EPA's Risk Reduction Engineering Laboratory (RREL) to assist permit writers and designers in evaluating earth dike stability. GARDS details the basic technical concepts and operational procedures for the analysis of site hydraulic conditions, dike slope and foundation stability, dike settlement, and liquefaction potential of dike and foundation soils. It is designed to meet the expressed need for a geotechnical support tool to facilitate evaluation of existing and proposed dike structures at hazardous waste sites.

For additional information on seismic risk zones of the United States, the range of seismic parameters for source zones, and GARDS, the reader is referred to EPA, 1986c.

7.5.5.3 Slope Stability Design Plans

The design plans for dikes and cut slopes should show the design layout, cross sections portraying the proposed grade and bearing elevations relative to the existing grade, and details of the dikes or cut slopes, including all slope angles and dimensions. Materials present at the cut slope or to be used to construct the dike must be adequately characterized (see EPA, 1986b). This design configuration then must be evaluated for its stability under all potential hydraulic and loading conditions. If the stability analyses result in unacceptably low factors of safety, then the design must be modified to stabilize the slope. The revised design must then be evaluated to verify that it is sufficiently stable.

In addition, in a monofill or surface impoundment, often the cut slopes or dikes will not be identical around the entire perimeter of the unit. For this reason, it is important that the most critical slope or dike section be identified for analysis. Generally, the most critical section will be the steepest and/or the highest portion of the slope or dike. Particularly in a cut slope, however, the in situ materials may vary enough that the more critical slope may be shallower or flatter, but may be composed of weaker soils or may be subject to significant pore pressures or seepage from high ground-water levels.

7.5.6 Liner Systems

Current regulations for sewage sludge surface disposal sites (Part 503, Subpart C) do not require that land

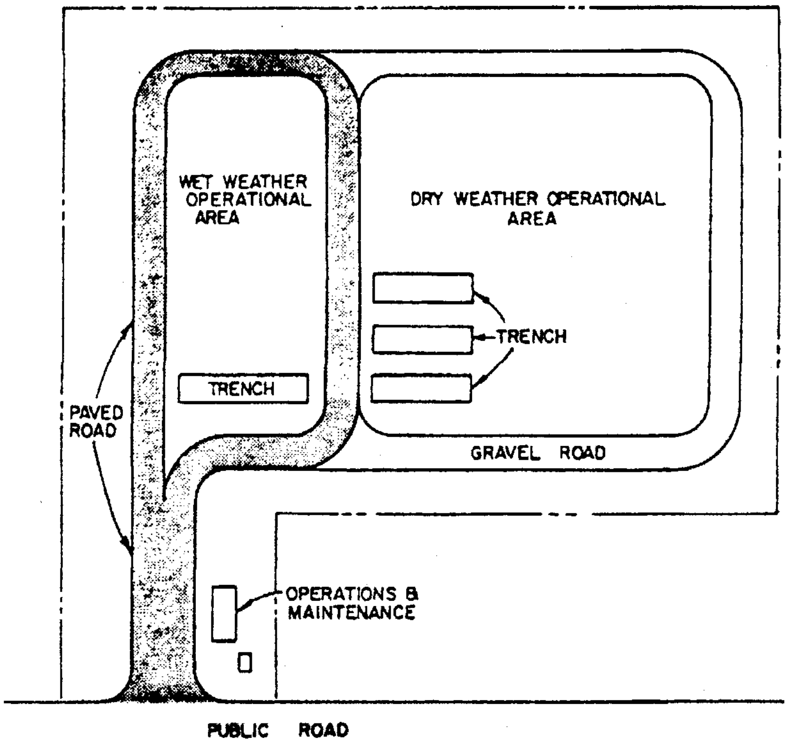


Figure 7-52. Special working area.

can occur that necessitate the ability to respond to calls for assistance.

7.9.6 Lighting

If dumping operations occur at night, portable lighting should be provided at the operating area. Alternatively, lights may be affixed to haul vehicles and onsite equipment. These lights should be situated to provide illumination to areas not covered by the regular headlights of the vehicle.

If the site has structures (e.g., employee facilities, administrative offices, equipment repair or storage sheds), or if there is an access road in continuous use, permanent security lighting might be desirable.

7.9.7 Wash Rack

For surface disposal units where operational procedures call for frequent contact of equipment with the sludge, a cleaning program should be implemented. Portable steam cleaning units or high-pressure washers may be used. A curbed wash pad and collection basin may be constructed to collect and contain contaminated wash water. The contaminated water may be either pumped to a septic tank/soil absorption system or dispersed with the sludge. The washing facility should be used to clean mud from haul vehicles, in order to keep sludge and mud off the highway.

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