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Guide to Technical Resources for the Design of Land Disposal Facilities

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PAGE 001

Table of Contents

Table of Contents (continued)

Table of Contents (continued)

Table of Contents (continued)

Table of Contents (continued)

CHAPTER 1.0

Introduction

Subtitle C of the Resource Conservation and Recovery Act (RCRA) of 1976, as amended by the Hazardous and Solid Waste Amendments (HSWA) of 1984, establishes requirements for landfills and surface impoundments to ensure that land disposal of hazardous waste in such units is conducted in a manner protective of human health and the environment. Performance standards and minimum technology requirements have been promulgated by EPA at Title 40 Code of Federal Regulations (CFR) Part 264 for new and existing units. These standards and requirements are implemented through permits issued by authorized states or EPA in accordance with the regulations of 40 CFR Part 122 through 124. Specific information requirements for RCRA permit applications have been promulgated at 40 CFR Part 270.

1.1 Purpose

EPA has issued numerous technical documents intended to assist preparers and reviewers of permit applications for hazardous waste land disposal facilities, including RCRA Technical Guidance Documents, Permit Guidance Manuals, and Technical Resource Documents. Some of these documents provide extensive detail on a select number of specific technical subjects related to the design and operation of land disposal facilities, while others provide broad guidance on RCRA permitting issues. The objective of these documents is to facilitate the expeditious preparation and processing of RCRA permit applications and to achieve consistency in permitting decisions.

EPA is concerned, however, that permit applicants and reviewers may not be familiar with all of the technical documents which the Agency has issued and may not be taking advantage of the information which they offer. EPA recognizes a need to provide a concise directory of information resources which are available and to suggest how these resources may be effectively used in the RCRA permitting process.

The purpose of this Guide is to direct permit applicants and permit application reviewers to the EPA documents which may be helpful in answering specific technical questions which often arise during permit application preparation and processing. Non-EPA technical literature has also been included in this Guide as appropriate. It should be noted that the list of non-EPA documents for any one subject may not be all inclusive. Other literature, i.e., books, may be as appropriate. The Guide does not provide detailed guidance on each regulatory standard for RCRA permit applicants but rather provides an overview of technical considerations.

1.2 Scope

Since this is a Guide to other information sources, it contains very limited primary information itself. To maximize its usefulness as a Guide, emphasis has been placed on brevity and conciseness. While the Guide generally does not discuss in detail the information provided in the primary sources, it directs the reader to the locations within these sources where specific technical subjects are addressed. (The references, as shown in the text, generally refer to the paragraph in which they appear. Where references appear within a paragraph, they refer to the text that immediately precedes them.)

The topics included in this Guide are limited to key performance standards and minimum technology requirements specified in 40 CFR Part 264 for hazardous waste landfills and surface impoundments. Each topic is addressed in an individual chapter as follows:

- Foundations (Chapter 2.0)
- Dike Integrity and Slope Stability (Chapter 3.0)
- Liner Systems (Chapter 4.0)
- Cover Systems (Chapter 5.0)
- Run-on/Run-off Controls (Chapter 6.0)

While the subjects addressed in this Guide are those which frequently arise in preparing and reviewing permit applications, the information and references provided in each chapter may also be useful in designing and operating other types of land disposal units (i.e., waste piles and land treatment units) and land disposal facilities for non-hazardous wastes.

1.3 Use

It is important to note that environmental performance standards in the regulations are qualitative objectives designed to protect human health and the environment and to guide the evaluation of permit applications. There may be a variety of technical approaches to designing, constructing and operating landfills and surface impoundments to accomplish these objectives.

Therefore, permit applications must provide a demonstration that the design, construction and operation of the specific land disposal units covered will meet these objectives. Such demonstrations must be made on a facility-specific basis. The general process for these demonstrations is summarized as follows:

1. Identify and justify the specific technical parameters which are important to attainment of the performance standard;

2. Identify and justify the methodologies used in determining whether such technical parameters are within an acceptable range of values. This could include, for example, test procedures, mathematical calculations, and/or references to commonly accepted engineering standards or EPA guidance; and

3. Demonstrate that each technical parameter falls within an acceptable range using the methodologies selected.

This Guide is organized in accordance with this process. The first section in each chapter provides a brief summary of the existing regulations (as of May 31, 1988) under 40 CFR Part 264 (the performance standards and minimum technology requirements) and 40 CFR Part 270 (RCRA permit application informational requirements) which correspond to the technical area covered in the chapter. The first section of each chapter also presents major technical parameters which are commonly considered in evaluating permit applications with respect to each performance standard. In subsequent sections of each chapter, the reader is referred to those technical documents which can be helpful in selecting evaluation methodologies and in determining acceptable ranges for these parameters. Each of the chapters are meant to be free-standing documents, hence, there may be some duplication of information from chapter to chapter. This duplication is necessary in order for the individual chapters to flow properly.

1.4 Update

This document is intended to be practical and informative. It is requested that Guide users submit ideas and/or suggestions to EPA, at the following address, regarding ways this document can be improved, including additional information sources they have found to be helpful in the preparation and review of permit applications:

Risk Reduction Engineering Laboratory
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Requirements for liners and leachate collection and removal systems are currently being revised. On March 28, 1986, EPA proposed a rule implementing minimum technology requirements of the Hazardous and Solid Waste Amendments of 1984 (HSWA) for double liner systems and leachate collection systems. Following proposal of these regulations, EPA collected data characterizing and comparing the performance of compacted soil bottom liners and composite (soil/flexible membrane liner) bottom liners. The data indicated that the use of a flexible membrane liner improved the performance of a composite bottom liner over that of a compacted soil liner, with respect to leachate collection efficiency, leak detection capability, and leakage both into and out of the bottom liner.

On April 17, 1987, EPA made available the background document presenting the data on bottom liner performance and draft minimum technology guidance documents on single- and double-liner systems. EPA proposed stronger regulations for double liners and leak detection systems on May 29, 1987.

When these regulations are promulgated, it may be necessary to update this Guide accordingly. Chapter 4.0, which addresses low-permeability soil liners, flexible membrane liners, and leachate collection/leak detection systems is most likely to be affected by these regulatory changes.

Chapter 2.0
Foundations

Proper subsoil foundation design of a land disposal system is critical because liner system components, especially leachate collection pipes and sumps, can be easily damaged by stresses caused by foundation movement. Permit applications must include a comprehensive evaluation of subsoil foundation conditions, followed by a demonstration that the foundation design will minimize the effects of foundation movements on the rest of a unit's components.

2.1 Regulations and Performance Standards

The regulations governing foundations provide a performance standard rather than a design standard. The performance standards in 40 CFR 264.221(a)(2) for surface impoundments and 40 CFR 264.301(a)(1)(ii) for landfills state that foundations must be "capable of providing support to the liner and resistance to pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression or uplift."

Foundations for hazardous waste land disposal facilities should provide structurally stable subgrades for the overlying facility 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 facility components (Reference 1, p. 12)

In addition, likely seismic activities at the location must be confirmed. The jurisdictions where the seismic location standard is applicable are designated at 40 CFR 264.18(a). However, regardless of whether the facility is located in one of these jurisdictions, it is advisable to design foundations capable of withstanding maximum likely earthquake events.

The foundation analysis presented in a permit application should assess the potential for, and present calculated estimates of, settlement, compression, consolidation, shear failure, uplifts, liquefaction of the foundation soil, and the potential for hydraulic and gas pressures on the foundation. Typically, the analysis should provide geologic data, geotechnical data, hydrogeologic data, and seismic setting information. The following sections will describe the type of information and analyses needed to evaluate the foundation. The references that are cited describe how to evaluate the analyses.

Exhibit 2-1 summarizes the types of information and technical parameters commonly included in RCRA permit applications for landfills and surface impoundments to demonstrate that the foundation performance standard is met.

The steps normally taken to prepare such a demonstration are as follows:

- Preparation of a final design of the units, including design drawings showing their location on the site, their depth, configuration and dimensions, and their position relative to existing and final grade;
- Performance of a location-specific site investigation;
- Laboratory analyses of soil samples obtained during the site investigation;
- Analysis, as appropriate, of settlement potential, bearing capacity, hydrostatic or gas uplift pressures, liquefaction potential, and subsidence and sinkhole potential; and
- A Construction Quality Assurance Plan that identifies the level of inspection and testing necessary to construct the foundation to the specifications used in the design.

The following sections discuss these steps in detail, with specific instructions on how to evaluate the information provided in a permit application.

2.2 Site Investigation

Adequate site investigations are necessary to ensure that the foundation design is developed to accommodate expected site conditions. Site investigations are designed to establish the in-situ subsurface properties, site hydrogeologic

Exhibit 2-1. Types of Information Used to Demonstrate That the Performance Standard for Foundations is Met

Information	Typical Parameters
Description of Foundations	Description of: • General foundation design • Foundation materials • Include geological and construction drawings indicating bearing elevations
Subsurface Exploration Data	Detailed engineering characteristics of: • Subsurface soil • Bedrock • Hydrogeologic conditions
Subsurface Exploration Data	Engineering characteristics of foundation materials verified through procedures including: • Historical data • Test borings • Test pits or trenches • In situ tests • Geophysical exploration methods
Laboratory Testing Data	Test results for: • Index testing • Hydraulic conductivity • Shear strength • Compressibility
Engineering Analyses	Engineering analyses using data obtained through subsurface explorations and laboratory testing including, as appropriate: • Settlement potential • Bearing capacity • Stability of cut or constructed slopes • Potential for excess hydrostatic or gas pressure • Seismic conditions • Subsidence potential • Sinkhole potential • Liquefaction potential
Analysis of Settlement Potential	Estimates of total and differential settlement, including: • Elastic settlement • Primary consolidation • Secondary compression
Analysis of Bearing Capacity	Analysis of allowable bearing capacity and comparison of required bearing capacity based on actual loading

(continued)

Exhibit 2-1. Continued

Information	Typical Parameters
Analysis of Stability of Landfill Slopes	Analyses of static and dynamic cases for: • Excavated slopes • Embankment slopes • Slopes including liners and/or cover • Drained and/or undrained conditions
Analysis of Potential for Hydrostatic Pressures	Estimates of potential for bottom heave or blow-out due to unequal hydrostatic or gas pressures.

characteristics and the area seismic potential, all of which are critical to facility design (Reference 1, p.13).

2.2.1 *Foundation Description*

Foundation design procedures are site specific and very often are an iterative procedure. A typical preliminary foundation description should include:

- the geographic setting;
- the geologic setting;
- ground-water conditions;
- soil and rock properties;
- surface-water drainage conditions;
- seismic conditions; and
- basis of information.

Site plans should include the 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 be performed as near as possible to the units, if not within their boundaries. Some other critical elements of the foundation design that need to be addressed prior to completion of the site investigation are the foundation design alternatives, the foundation grade, the loads exerted by the unit or the foundation, and the preliminary settlement tolerances.

2.2.2 *Subsurface Exploration Programs*

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 hydrogeologic characteristics.

Reference 2, p. 5-3 and Reference 13 provide a strong guidance for planning subsurface exploration programs. The following list provides details of the elements of a subsurface exploration program:

- Relate the site geology to the regional geological setting;
- Provide analysis of the engineering properties of representative subsurface samples;
- Establish in-place subsurface characteristics that include depth to bedrock, and the presence of features that can act as failure planes or hydrogeologic pathways;
- Identify bedrock characteristics such as lithology, orientation, extent of weathering, fractures, joints and solution cavities; and
- Establish the hydrogeologic site characteristics such as depth of the water table; horizontal and vertical flow components; hydrogeologic pathways; seasonal variability; and the location, use, and type of aquifers present.

Subsurface exploration programs can utilize both indirect and direct methods. Indirect investigation methods include geophysical techniques (e.g., electrical survey methods, ground-penetrating radar and seismic refraction). These methods do not require drilling or excavation. The selection of the proper geophysical techniques is dependent on the geologic settings. (Reference 2, pp. 5-4 and 5-5). While geophysical procedures can provide large amounts of data at a lower cost, they require careful interpretation which must be done by qualified experts only. Furthermore, geophysical data must be verified by direct procedures such as borings or test pits.

Direct investigation methods include drilling boreholes and wells and excavating pits and trenches. Direct methods allow the site geologic conditions to be observed 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 should also record the intervals for, and the results of, any field hydraulic conductivity testing conducted in the borings.

Direct methods allow the investigator to obtain 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 water content. The thin-walled tube sample provides an undisturbed sample that can be used for a wide variety of laboratory tests; however, its use is limited to certain soil types and conditions.

The scope of the subsurface exploration program will vary depending upon 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. However, typically, 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. 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 (Reference 2, p. 5-6). Typically the hydrogeologic conditions are identified as part of the ground-water monitoring program.

2.2.3 Laboratory Testing Data

Laboratory testing for foundations may include the following (Reference 2, Chapter 3):

- Atterberg Limits,
- Grain size distribution,
- Shrink/swell potential,
- Cation exchange capacity,
- Mineralogy,
- Shear strength,
- Dispersity,
- Compressibility,
- Consolidation properties,
- Density and water content, and
- Hydraulic conductivity tests.

Soil index properties are simplified tests that provide indirect information about the engineering properties of soils beyond what can be gained from visual observations. Although the correlation between index properties and engineering properties is not perfect, it is generally adequate for QC purposes (Reference 2). Index property tests commonly used to screen soils are described below.

Atterberg Limits include tests to establish the liquid limits and the plastic limit of a soil (Reference 8). These tests are commonly used along with grain-size distribution, for monitoring changes in soil type. A significant change in Atterberg limits usually reflects a change in important engineering properties, such as the relationship among water content, density, compactive effort, and hydraulic conductivity.

Grain-size analysis is another important screening test for changes in soil composition. The percentage of silt and clay-size particles and the overall particle size distribution of a soil affects its engineering properties, especially hydraulic conductivity and strength. Rough estimates of grain size may be obtained through manual estimates (Reference 3; ASTM D 2488) and may be sufficient for screening. A 200-mesh sieve may be used to separate coarse (sand and gravel) and fine (soil and clay) particles. More detailed grain-size distributions may be obtained by sieving the coarse fraction and by using several settling methods (hydrometer, decantation, or pipette) for the fine fraction (Reference 3; ASTM D 422). Again, it is important to monitor carefully for soil-type changes as backfill material is being placed (Reference 2).

Soil index properties, Atterberg limits and grain-size distribution, are simplified tests that provide indirect information about the engineering properties of soils beyond what can be gained from visual observations. Although the correlation between index properties and engineering properties is not perfect, it is generally adequate for construction QC purposes (Reference 1). These two index property tests commonly used to screen soils are described below.

2.2.4 Seismic Conditions

Seismic analysis is particularly critical when there is a high potential for liquefaction to occur, such as in seismically-active areas underlain by loose, saturated sands and silts. Many regions in the country that have experienced earthquake activity should have information on the frequency and magnitude of earthquakes. There may also be established local standards for the design of structures. Generally, earth structures can be designed to withstand the vertical and horizontal accelerations experienced during such design earthquakes. A more detailed discussion of methods for evaluating site seismic parameters is presented in Chapter 3.0 of this Guide.

2.3 Design

Foundations are designed to provide structural support and to control settlement. Foundations must also be designed to withstand hydrostatic and gas pressures.

2.3.1 Waste and Structure

The engineering analysis for foundations is based on subsurface conditions; however, the results of these analyses are based on loading conditions. In order to perform the appropriate engineering analysis to demonstrate the adequacy of the foundation, the permit application should provide an accurate estimate of the loadings (including both structure and waste), plans showing the structure's shape and size, the expected waste characteristics and volumes, and the foundation elevations.

2.3.2 Settlement and Compression

The performance standards require that the foundation be capable of preventing failure of the liner system due to settlement and compression. Therefore, it is important that the permit application provides an analysis 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 and leachate collection and recovery systems to maintain their integrity under the expected stresses.

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 a land disposal 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 (Reference 4 and Reference 10).

Total settlements of a few inches or less are usually not a problem for soil liner foundations, since most are sufficiently thick and flexible to withstand some differential settlement of the foundation. As long as the topography is fairly uniform and significant subsurface heterogeneities are not present, differential settlement should be minimal. Foundation settlement analyses based on the site's subsurface conditions (determined during site investigation) should be conducted during the design of the facility. These analyses should take into account the loadings of all facility components on the foundations, including footings for pile-type structures such as leachate collection risers, which, if improperly designed, can be forced into or through the liner. Compensated foundation, which implies that the weight of soil extracted from the site balances the weight of fill material, also can be used as part of the design to minimize subgrade settlement. In addition, the expected differential settlement should be compared to the design slope of the leachate collection system to ensure the latter's adequacy is maintained (Reference 2, p. 5-14).

Landfill 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. The ability to predict the extent of settlement depends upon the type of process anticipated to cause settlement. There are several settlement processes, each of which should be considered in a land-based unit design. These are discussed in the following paragraphs and include:

- Primary consolidation,
- Secondary compression, and
- Elastic Compression.

Primary consolidation, which is typically a reduction in void ratio due to removal of pore fluids by mechanical loading, generally occurs in saturated fine-grained soils according to the consolidation theory developed for soil. Basically, the theory states that the rate and amount of compression is equal to the rate and amount of pore fluids squeezed out of the soil (Reference 5). The classic Terzaghi theory for one-dimensional consolidation of a soil is discussed in Reference 6, at page 17.

Primary consolidation of soils by lowering of the water table has been identified as an additional cause of ground subsidence in some locations. The effect of lowering the water table in a soil is to surcharge the soil particles by increasing the effective stress (the vertical stress minus the pore water pressure) through a decrease in pore pressure (Reference 6, p. 17).

Secondary compression is the gradual settlement from creep under essentially constant load. It depends upon the applied load and the chemical and physical nature of the soil particles. Secondary compression is more irregular and less predictable than primary consolidation and may be significant in settlement of plastic clay soils, heterogeneous fill materials, organic materials, and other compressible materials. Although secondary compression occurs at the same time as primary consolidation, secondary compression is usually taken into account at later times in the loading history of the fill when primary consolidation is complete and the applied stress is transferred from the pore fluids to the soil skeleton (Reference 2, p. 5-15 and Reference 11).

Elastic compression occurs when the volume of solids is reduced. The effect of elastic compression of mineral soils is minimal; however, it may be a major concern with organic soils, soluble materials, and materials subject to chemical attack. This type of compression is highly irregular and is influenced by a number of environmental factors that make it difficult, if not impossible, to predict and are, therefore, not typically considered in geotechnical practice (Reference 2, p. 5-15).

Both theoretical and empirical approaches are utilized for predicting settlement. The theoretical methods are based on elastic theory and summation of strains. Empirical or semi-empirical methods include performing load tests and penetration tests in the field. Theoretical methods should be used only in conjunction with empirical methods that provide field verification (Reference 4, Chapters 8 and 14, and Reference 6, Chapter 9:3).

The elastic theory applies to soil only in a very approximate way. Soil itself is not elastic; however, elastic theory provides a convenient means to estimate stresses induced within a soil mass by applied loads. Knowing these stresses allows the engineer to compute the strains, and by adding up the strains along any vertical line, the settlement of the surface can be computed (Reference 4, Chapters 8 and 14).

2.3.3 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 can also be caused by hydrostatic pressure where the latter exceeds the confining pressure of the foundation and liner (Reference 2, p. 5-15).

Solutions to these problems include various systems that are available to lower the hydraulic head at the facility. 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 (Reference 2, p. 5-16).

2.3.4 Bearing Capacity

For waste disposal units, the major issue of concern for foundations is differential settlement. However, for structures such as tank foundations, leachate risers, etc., an additional area of concern is bearing capacity failure (Reference 6, Chapters 9:2 and 9:3).

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 must be established for the foundation soil. 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. Reference 7, Chapter 10, 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 (Reference 4, Chapter 14; Reference 6, Chapter 9:2 and Reference 12).

Several types of structural foundation failures can occur that are highly site specific. These failures depend on subsurface conditions and loading type and conditions. The various types of foundation failures that can occur are discussed in Chapter 9 of Reference 7, Chapter 9:2 of Reference 6 and Chapter 14 of Reference 4. In addition, for cases where the foundation consists of soft soils, special care must be taken to ensure that local shear failures do not occur due to equipment movement during placement of the liner system or the waste.

Many large metropolitan areas have records of allowable design soil pressures that have been successful and also those that have failed. These are called presumptive bearing pressures because they are based on past performance that the soil can support such a pressure without experiencing a bearing capacity failure or excessive settlement (Reference 6, Chapter 9:5).

These values are not defendable for design work and are not to be considered a performance standard. For example, the sand pressures usually provided are highly dependent on footing size; the soft-to-firm clays need an analysis based on site-specific conditions and soil properties; and the stiff-to-hard clay assumes no fissures. However, the presumptive values do provide a general guidance for the reviewer of typical values to be expected. In short, they provide a reference point, but not a hard and fast design criterion. (Reference 7, Chapter 10:5)

2.4 Excavations

Most hazardous waste units are constructed below existing grade. Therefore, most sites must be excavated to final foundation grade. If the total depth of excavation exceeds approximately ten feet, a slope stability analysis of the excavated slopes should be made. Slope stability analyses are discussed in Chapter 3.0, and generally the same procedures apply to cut slopes, except that lower factors of safety are acceptable.

2.5 Quality Assurance

Once the design of the foundation has been completed in accordance with acceptable standards, the foundation's construction can begin, as designed and specified, following strict quality assurance procedures. The primary quality assurance issues for foundations are to assure the adequacy of the subgrade and, if necessary, the compacted fill through density testing. A brief discussion is provided below on EPA's guidance for construction quality assurance procedures, as provided in Reference 1. This is followed by a discussion of field density testing that can be performed to establish adequate subgrade and compaction (Reference 2, p. 3-26).

2.5.1 General Quality Assurance Procedures

Reference 1 provides technical guidance regarding quality assurance procedures during the preconstruction, construction and post-construction procedures. In addition, Reference 9 provides a summary of items for inspection of old or new concrete. During the preconstruction phase, it is especially important for all construction quality assurance personnel and the construction contractors to review site investigation information to familiarize themselves with the expected site conditions upon which the facility designs were based. This will help ensure their ability to identify any unexpected site conditions encountered during construction (Reference 1, pp. 12-15).

2.5.2 Materials

Soil and rock underlying the facility must possess adequate strength to support the expected loading. If tests on samples of the materials examined in the laboratory and on-site bearing tests show inadequate properties, the site design and construction plans should include specifications that provide for preparation of an adequate foundation. If appropriate, samples of materials from potential borrow areas to be used to construct the foundation should be analyzed to determine their acceptability for the specified design. This information is used to identify desirable materials and reject undesirable materials. The principal concern is to verify that the specified materials of any load-bearing foundation are specified in enough detail to compare with the characteristics shown to be required by the engineering analysis. (Reference 2, pp. 1-4).

2.5.3 Subgrade Requirements

Visual observation of the subgrade is necessary to assure that the foundation is constructed as designed. The site engineer needs to ensure that all soft, organic and otherwise undesirable materials are removed. This can be done by proof rolling with heavy equipment to detect soft areas. As outlined in Reference 1, various tests are available to verify the condition of the foundation subgrade.

In addition, the site engineer should inspect soil and rock surfaces for rock joints, clay fractures and depressions. These features should be adequately filled. If sand seams are encountered, they should be removed and refilled with compacted material (Reference 1, p. 13).

2.5.4 Compaction Requirements

If required, selection of backfill material that can be compacted to the required density and permeability involves a series of laboratory tests of the engineering properties of the candidate materials. One such engineering characteristic is the water content/density relationship which is established for the material by compacting samples of the material at various water contents with a set compactive effort (Reference 2; pp. 3-21 to 3-25). A standard method has been adopted and described in ASTM standard test method D698 (Reference 8; ASTM D698).

Based on the compaction test data, compaction specifications should indicate the minimum percent of maximum density and the water content relative to the optimum water content at which the soil should be compacted. Soils have different characteristics at water contents above, at, or below the optimum water content. For instance, clays compacted on the wet side of the optimum water content are less permeable than those compacted on the dry side. On the other hand, clays compacted dry of optimum are stronger and have a higher stress-strain module than do clays compacted wet of optimum (Reference 2, pp. 3-21 to 3-25).

2.5.5 Concrete Requirements

In some cases, a hazardous waste management unit may be placed on a concrete surface. The concrete might be new (poured recently with the intent of being the FML supporting surface) or old (an older structure that is being retrofitted with an FML) (Reference 9, p. 4-17). Old concrete must be checked very carefully, because it is more likely to have cracks, surface chipping, and a rougher surface. Old concrete is also more likely to chip and crack when drilling is required to set items like FML anchor bolts. The effects of surface irregularities may be minimized by the use of various coating materials or by covering with a geotextile (Reference 9, pp. 4-17).

New concrete must be allowed to age in order to obtain the strength needed to set items like FML anchor bolts. In addition, any wax-type curing compound used must be removed prior to FML placement, since sealing compounds (adhesive, cements, and caulks) will not adhere to this type of surface. If surface voids exist, they must be eliminated by sacking with cement grout (Reference 9, p. 4-19).

2.5.6 Placement

During placement of soil materials, the soil is spread uniformly as specified. The loose lift thickness of the soil should be measured systematically over the entire site, with a marked staff or shovel blade, and survey levels should be made every few lifts for verification and documentation of fill thickness. Following spreading, the backfill material is disked or tilled to break up large soil aggregates and to homogenize the material (Reference 2, pp. a-6 to a-9).

2.5.7 Compaction Equipment

The principal types of compacting equipment are the smooth wheel roller, the rubber-tired roller, the sheepsfoot roller, and the vibratory compactor. The latter would be the most effective piece of equipment for compacting coarse-grain, cohesionless soils. However, vibratory rollers are the least effective compactors for cohesive soils. Rubber-tired rollers with high tire pressures and sheepsfoot rollers are effective for cohesive soils. Sheepsfoot rollers are particularly effective at bonding of lifts during compaction of cohesive soils. Reference 6 provides a detailed discussion of compactive equipment and methods.

2.5.8 Field Density Testing

Two traditional methods are used for measuring density in the field. In one type of test, a small hole is dug in the compacted fill and the excavated material is saved and weighed. The volume of the hole is measured by filling it with sand or liquid with a device that measures the amount of material required to fill the hole. The sand cone and rubber balloon methods are examples of this type of test. Another technique is to drive a hollow cylinder into the fill, remove a core, trim it to a known volume, and then determine its weight. This drive-cylinder method and the sand cone and rubber balloon methods take time because the sample must be oven dried before the dry density can be determined (Reference 2, p. 3-26).

Nuclear probes (Reference 8, ASTM D-2922 and D307) offer a faster and more convenient method for measuring field density and water content than the traditional methods and are presently widely used for earthwork compaction quality control. Nuclear gauges are designed to give very rapid measurements of density and moisture content. The operation of nuclear gauges is discussed in Reference 2, p. 3-29. In order to compensate for the soil compositions that may affect the neutron response, it is customary to calibrate the nuclear density gauge against oven dried water content measurements by the appropriate laboratory test method (Reference 8; ASTM D2216).

2.6 References

1. Technical Guidance Document: *Construction Quality Assurance for Hazardous Waste Land Disposal Facilities*; Hazardous Waste Engineering Research Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, Ohio 45268; EPA Contract No. 68-02-3952, Task 32; October 1986.

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Chapter 3.0
Dike Integrity and Slope Stability

Most landfills 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. Surface impoundments are often designed to achieve some balance of cut-and-fill, with the excavated soils used to construct the dikes. Landfill cells are excavated below grade in order to provide operating cover materials and to allow for restoration of the site after filling.

These excavated slopes and earthen dikes are vulnerable to stability failures via several mechanisms that will be discussed in this chapter. Slope and dike failures at hazardous waste management units are potentially very serious; a surface impoundment failure can allow the sudden release of large amounts of hazardous waste to ground water and surface waters, and a landfill slope failure can seriously damage the liner system, allowing releases of waste and leachate to surrounding soils and ground water.

For these reasons, earthen dikes must be carefully designed and excavated slopes must be carefully evaluated to assure that they are sufficiently stable to withstand the loading and hydraulic conditions to which they will be subjected during the unit's construction, operation and post-closure periods. This chapter will discuss the regulatory requirements that apply to slope stability issues and will describe how to design and evaluate dikes and slopes for stability.

One of the apparent differences between landfill and a surface impoundment unit is that of solid vs. liquid wastes. From the viewpoint of stability, however, there is no real difference; the forces on a slope exerted by liquids are modeled in a manner identical to those of solids. Another issue related to the impoundment of liquids is that of seepage through the dikes, causing piping or hydrostatic uplift pressures; however, this seepage condition is modeled in a manner identical to the condition of ground-water seepage at a cut slope. Since the failure mechanisms are similar for dikes and excavated slopes, these two configurations will be discussed concurrently.

3.1 The Regulations and Performance Standards

The regulations for surface impoundments, 40 CFR 264.221(g), (Reference 1), require simply that massive failure of dikes be prevented through adequate design, construction and maintenance. This is a performance standard only; the regulations do not contain design standards. For landfills, there are no specific slope stability regulations; however, the regulations at 40 CFR 264.301 require that a liner system in a landfill be placed upon a foundation or base that will prevent the failure of the liner.

In order to demonstrate that the entire liner system is placed upon a stable base, the stability of the slopes must be demonstrated.

The surface impoundment regulations (Reference 1, 40 CFR 270.17 and 264.226) also require that the structural integrity of each dike be certified by a qualified engineer. Exhibit 3-1 summarizes the types of information and technical parameters commonly used to demonstrate that the performance standard is met.

3.2 Design and Materials Selection

Slope stability failures usually occur in one of three major modes, depending upon the site soils, slope configuration, and hydraulic conditions (Reference 2). These three major failure modes are the following:

- rotation on a curved slip surface approximated by a circular arc.
- translation on a planar surface whose length is large compared to its depth below ground.
- displacement of a wedge-shaped mass along one or more planes of weakness in the slope.

Exhibit 3-2 illustrates basic concepts of translational and rotational failures, and Reference 2, Chapter 7 shows more examples of these potential slope failures in natural and in cut and fill slopes.

Slope failures occur when sliding forces from the weight of the soil mass itself and external forces

Exhibit 3-1. Information Typically Submitted to Demonstrate Satisfaction of Performance Standards for Dike Integrity

Information	Typical Parameters
Description of Dike Design	Data and/or drawings specifying: • Design layout of dikes • Design layout of components • Materials of construction • Elevations of critical points
Demonstration of Stability	Capability to withstand expected static and dynamic loadings and the effects of erosion
Demonstration of Erosion and Piping Protection	Demonstration of minimization of erosion and prevention of failure considering the erosion potential of: • Rainfall • Surface water runon and runoff • Contact between impounded wastes and dikes • Potential leakage and piping through dikes • Potential leakage and piping along conduits or structures through dikes
Analysis of Subsurface Conditions	Engineering characteristics of foundations and soil dike materials through testing and subsurface explorations, such as: • Test borings • Test pits or trenches • In situ tests • Geophysical methods • Strength and consolidation tests on foundation materials • Permeability
Stability Analyses	Description and results of stability analyses for the following conditions, as appropriate: • Foundation soil bearing failure or settlement • Failure in dike slopes • Failure of impoundment cut slopes • Build-up of hydrostatic pressure due to failure of drainage system, dike cover, and liner • Rapid drawdown
Construction Specifications	Procedures for dike construction
Engineer Certification	Certification of integrity of dike designs and construction

including waste 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 (Reference 3, Section 12-1):

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

When a stability analysis is performed, a slope is analyzed for one or more of several potential modes of failure, including rotational, translational and wedge, as appropriate. A safety factor is obtained for each mode, and the lowest FS is the most critical.

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-inducted piping failure. Safety factors are determined in a manner similar to the three modes. These failure modes will be discussed in greater detail in Section 3.2.3.

Exhibit 3-3 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.

In order to evaluate an existing, conceptual, or final slope design, the designer or reviewer must consider the following factors:

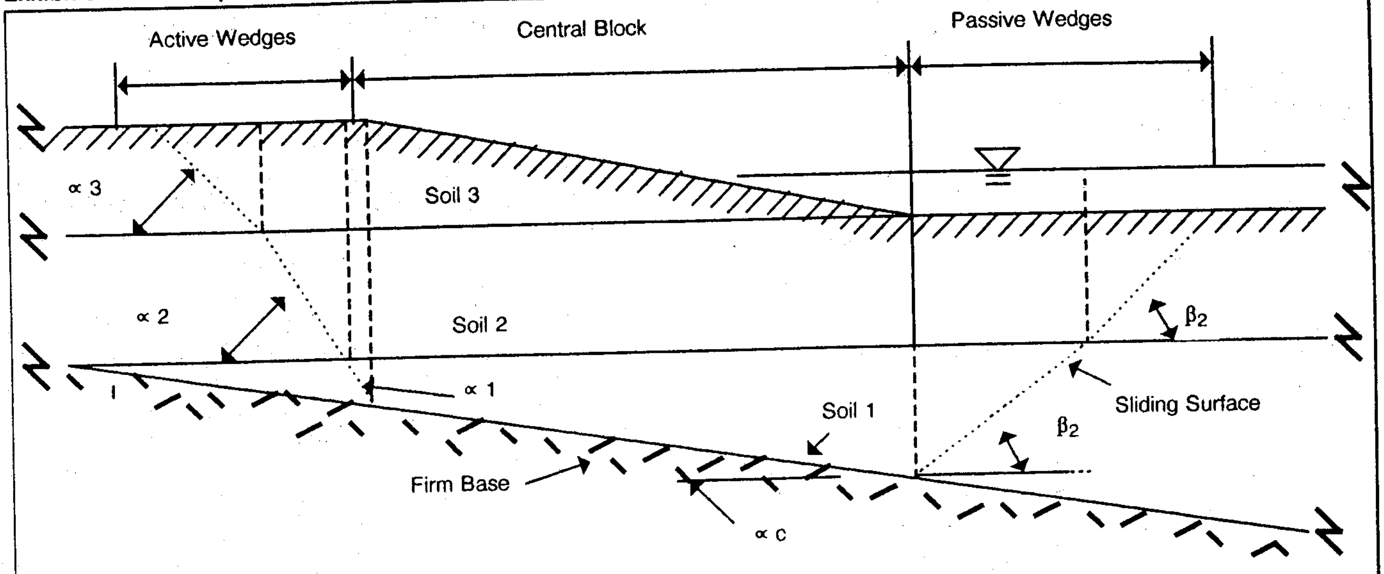
- the adequacy of the subsurface exploration program
- the stability of the dike slopes and foundation soils
- liquefaction potential of the soils in the dike and the foundation
- the expected behavior of the dike when subjected to seismic effects
- potential for seepage-induced piping failure
- differential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

The following sections will discuss each of these factors, including the use of an EPA-developed computer model called GARDS, Geotechnical Analysis for the Review of Dike Stability (Reference 4).

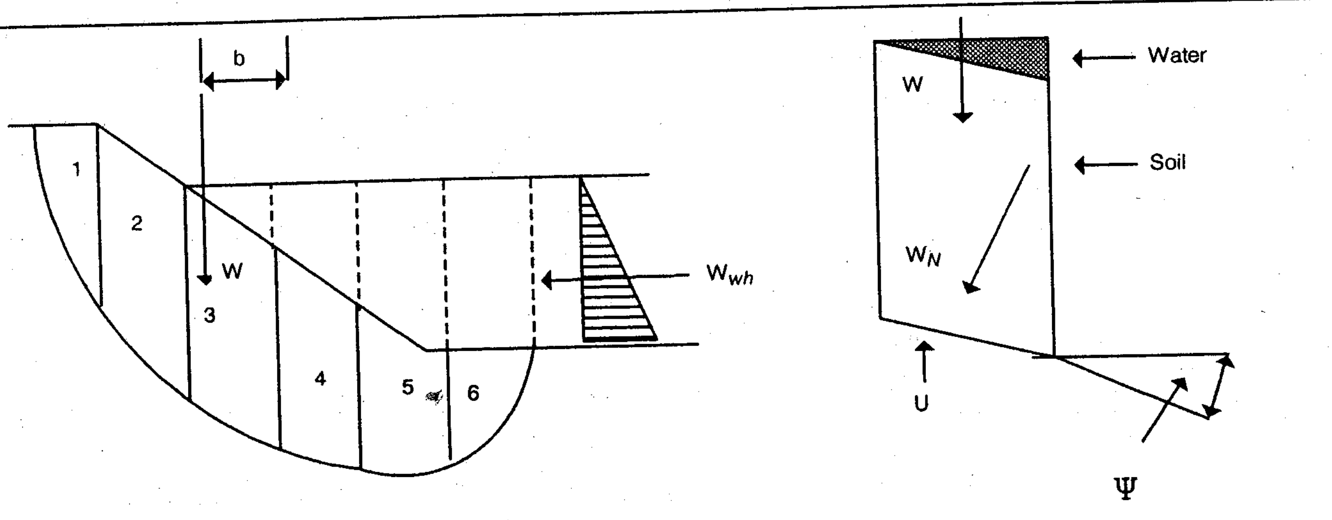
3.2.1 Subsurface Exploration Program

Site investigations are conducted to delineate a site's topography, subsurface geology and hydrogeology. They 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. These investigations include

Exhibit 3-2. Conceptual slope failure modes.



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)

field testing performed during drilling programs and laboratory testing performed on field samples. Of particular importance in some circumstances are laboratory strength tests performed on soil samples to determine the strength of the foundation and embankment soils under the expected conditions of saturation and consolidation. Site investigations include field exploration procedures such as remote sensing techniques, geophysical methods, test pits and trenches, and borings. The field exploration is followed by laboratory analysis of soil samples obtained during the field program. The field and laboratory data is then 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. (See Chapter 2 of this guide for additional discussion on field investigations).

Exhibit 3-3. Recommended Minimum Values of Factor of Safety for Slope Stability Analyses (Reference 4)

Consequences of Slope Failure	Uncertainty of Strength Measurements 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.

The number of borings or test pits required to characterize the subsurface is dependent on its complexity; a site with fairly uniform geologic conditions across the site can be sufficiently characterized with fewer exploratory probes than a more complex site. In any case, the test pits or borings must be performed at locations within or very near to the actual unit. Reference 2, Chapter 2 provides a discussion of field exploration, testing and instrumentation methods used to characterize a site.

For embankments constructed of on-site borrow materials, the borrow area should also be investigated to verify that it contains an adequate volume of acceptable material. This investigation will be very similar to that performed for excavated units, with the notable exception that all laboratory testing, i.e., strength, hydraulic conductivity, should be performed on remolded samples because the soils will be excavated and recompacted.

Hydrogeologic investigations are also necessary to determine the elevation of the water table at the site (including seasonal variability) and to locate, identify, and delineate hydrologic pathways (e.g., fractures and sand seams) that can contribute to slope failure (Reference 5). The significance of hydrogeologic conditions concerning slope stability will be discussed further in Section 3.2.3.

Laboratory testing is conducted using representative soil samples. Testing, as appropriate to evaluate the embankments, the foundation area, and those areas under consideration as a source for borrow material, include Atterburg Limits (Plasticity Index, Liquid Limit), grain-size distributions, shrink/swell potential, shear strength, compressibility, consolidation properties, density and water content, moisture-density relationships, and laboratory hydraulic conductivity (Reference 5).

For slope stability analyses, the most critical soil parameter is that of shear strength. 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 (Reference 5). 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 which contains large particle sizes. Furthermore, in existing dikes, the type of material may make the obtaining of undisturbed soil samples near to, if not, 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.

Slope stability is also 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 (Reference 5):

- seepage quantity
- critical (highest) exit gradient
- potential for uplift of a clay liner due to excess pore pressures produced by a confined seepage condition

Hydraulic boundary conditions may reflect unconfined, 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 in Reference 13, Chapter 10.

3.2.2 Design

The design plans for dikes and cut slopes should show the design layout, cross-sections showing 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 or specified (Reference 5). 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 landfill 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. However, particularly in a cut slope, 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.

3.2.3 *Stability Analyses*

Slope stability analyses are performed for both excavated side slopes and above-ground embankments. Three analyses will typically be performed as appropriate to verify the structural integrity of a cut slope or dike; they are slope stability, settlement and liquefaction. Exhibit 3-4 indicates the minimum required soil parameter data usually needed to perform these analyses. Slope stability analysis requires the establishment of various site conditions including:

1) The soil shear strength conditions that represent actual site conditions (discussed in Section 3.2.1)

2) The steady state hydraulic boundary conditions occurring through the site's section (discussed in Section 3.2.1)

3) The seismic conditions established for the site area.

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. The latter is typically performed using a coefficient that approximates seismic conditions established for the site area. For large dikes in areas of major earthquakes, a more rigorous method of dynamic analysis may be warranted. When appropriate, the liquefaction potential of the foundation or embankment is also determined using seismic conditions established for the site area.

Analyses to establish total and differential settlement are also performed to ensure that the estimated settlement will not adversely impact the integrity of the unit and its components. The analysis of potential settlement is discussed in Chapter 2.0.

The slope stability analysis uses data from the site investigation and soil testing to perform either of two conventional slope stability analyses. The first is a rotational (circular slip surface) analysis and the second is a translational (plane slip surface or wedge) analysis. The translational wedge analysis applies primarily to stratified sections, especially where stratum boundaries are inclined or where a stratum with low shear strength exists. Even so, a rotational stability analyses may yield a lower Factor of Safety for the section and should always be checked (Reference 4).

3.2.3.1 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. 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 Factor of Safety is computed (Reference 4).

3.2.3.2 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 which form the base of one or more active (thrusting) wedges, a neutral or thrusting central block, and one or more passive (restraining) wedges. This analysis is based upon selection of a trial central block defined by the surface and subsurface soil layer geometry, followed by computation of the coordinates for the associated active and passive wedges (Reference 4).

3.2.3.3 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 overconsolidation ratio (Reference 4). A

Exhibit 3-4. Minimum Data Requirements for Stability Analysis Options (Reference 5)

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

detailed discussion of settlement analysis is provided in Chapter 2 of this Guide.

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 Reference 4.

3.2.3.4 Liquefaction Analysis

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

Factors which most influence liquefaction potential are: soil type, relative density, initial confining pressure, and the intensity and duration of earthquake motion (Reference 4). Reference 4 provides information on seismic risk zones of the U.S. and on the range of seismic parameters for source zones. Methods for estimating the potential for liquefaction are provided in the GARDS software package described in Section 3.2.3.5. Additional methods and charts for estimating the liquefaction potential can be found in References 14, 15, and 16, Chapter 11.

3.2.3.5 Geotechnical Analysis for Review of Dike Stability (GARDS)

A computer software package called Geotechnical Analysis for Review of Dike Stability (GARDS) 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 earth dike structures at hazardous waste sites.

The GARDS software package is available from RREL, and a technical manual explaining its operation, Reference 4, is also available. Both the software and this support documentation contain text explanations and graphic examples designed to guide the user through the customary steps of earth dike analysis. User-friendliness is accomplished through the use of menu selection of available program options, including data check and simplified editing procedures, automatic internal check of input parameter values, cautionary statements regarding the recommended sequence of program options, and error diagnostic statements with interactive instructions for corrective action.

GARDS is designed to guide the reviewer through the customary steps of earth dike analysis considering slope stability, settlement, liquefaction, hydraulic flow and pressure conditions. GARDS includes an internal automatic search routine to determine the critical failure surface for both rotational (slip circle) and translational (wedge) stability analyses; an internal, automatic search routine to locate zones of greatest liquefaction potential and to compute total and differential settlements of foundation soils; and internal finite element hydraulic analysis to determine the steady state piezometric surface through the section, including the case of an impermeable barrier such as soil liner; the ability to model excess pore pressure conditions produced by confined steady flow and evaluate slope stability and any resulting uplift conditions; and the ability to determine the maximum exit gradient which defines the potential for piping failure (Reference 4).

The GARDS user must identify the various site conditions which need to be investigated and select the appropriate combination of options which best models those conditions. GARDS offers the user six idealized hydraulic boundary conditions, three stability options (slope stability, settlement, liquefaction), and three soil shear strength options: Unconsolidated Undrained (UU); Consolidated Undrained (CU); and Consolidated Drained (CD). A limited amount of guidance logic has been built into GARDS to assist the non-specialist user in making decisions regarding the available analysis options (Reference 4).

GARDS incorporates summary output block which allows the user to obtain a hard copy of the input data and the results of all analyses run for the dike section under study. The critical factors of safety, failure circle center coordinates, radius, and plane failure line segment coordinates are all highlighted in the output listing, along with the computed differential settlements, liquefaction potential, and critical exit gradient. If an analysis was not run, this is indicated in a summary table at the end of the output listing.

3.3 Materials/Specifications

Material and construction specifications should be provided as appropriate for all load supporting embankments.

3.3.1 Subgrade Requirements

The subgrade requirements for slope stability are the same as these addressed in Section 2.4.1 for foundation materials.

3.3.2 Borrow Materials

The native soil at the facility excavated during foundation excavations is the ideal backfill material from the standpoint of cost and convenience. However, if the native soil is not suitable, a suitable soil from a nearby borrow source should be utilized (Reference 2). At a minimum, material specifications should provide the range of acceptable materials. All materials should then be required to meet the minimum requirements of the national specifications as verified through specified field testing.

3.3.2.1 Selection

Once potential borrow sources have been identified, the site should be investigated (see Section 3.2.1) to determine the amount of suitable materials present at the site and the degree of spatial variability of material properties in the soil deposits. The investigation results can also be used to plan an efficient extraction procedure for the materials (Reference 7).

As discussed in Section 3.4, representative samples of the borrow material are subjected to laboratory compaction and hydraulic conductivity tests to establish the relationships among water content, density, compaction effort and permeability (Reference 7).

When suitable soils are not available at an economic distance from the facility, the engineer may recommend blending an additive, such as bentonite, to the native soil in order to achieve the proper material properties and performance (Reference 7).

3.3.2.2 Test Fill

Laboratory results and design assumptions need to be verified in the field. This verification can be accomplished through a test-fill program. The test-fill program allows the engineer to establish the material, equipment and construction procedures required to meet the design requirements for the fill materials that comprise the dike. The test-fill program is also a convenient tool for evaluating critical performance standards such as shear strength, density, and permeability (Reference 7).

Test fills, if used, should be constructed for each borrow source and whenever significant changes occur in the material, equipment, or procedures used, to construct the soil liner (Reference 7). Samples of the test fill should be obtained for testing to assure that the materials meet the minimum specifications.

3.4 Embankment Construction

Embankment construction for landfills or surface impoundments involves standard earthwork construction practices. Dike construction activities include fill placement and compaction, drainage system construction, and implementation of erosion control measures (Reference 7).

3.4.1 Compacted Fill Construction

Compacted fill may be part of the dike core, the dike shell, or may constitute the entire dike. Critical construction activities include emplacement, conditioning, and compaction. To insure that these activities are conducted properly, the following measures must be taken (Reference 7, p. 16):

- Placing loose lifts to the thickness established during the test fill program
- Removing or reducing clod size material to a maximum size as determined in the test fill
- Providing uniform compaction coverage using the type of equipment and number of passes specified in the test fill program
- Ensuring uniformity of backfill material
- Protecting the surface lifts from desiccation or frost action
- Scarifying between compacted lifts
- Ensuring adequate connection between lifts

3.4.2 Drainage Systems Installation

Installation procedures and equipment for dike drainage systems are similar to those for leachate collection systems. The observations and tests that are necessary to monitor the installation of drainage system components are discussed in Section 4.4.3 of this guide (Reference 7, p. 39).

3.4.3 Erosion Control Measures

Erosion control measures are applied to the outer slopes of embankments and may include benches and vegetative covers. The construction activities necessary for ensuring the quality of erosion control measures are the same as those for topsoil and vegetation subcomponents of cover systems discussed in Section 1. (Reference 7).

3.5 Quality Assurance/Quality Control (QA/QC)

Observation of the construction process is the most effective approach to QC, coupled with a well-defined testing program. Beyond the minimum specified test frequency and spacing, visual observations are used to identify problem areas and to call for more intensive testing to document and delineate any substandard backfill areas. Typical items to be on the lookout for include wet spots, large clods in backfill material, effects of exposure to frost, erosive effects of heavy rains and surface water runoff, poor bonding between lifts due to lack of scarification, and inclusion of undesirable foreign objects. Remedial actions (e.g., removal and reconstruction) are then ordered for the substandard areas so delineated. A qualified inspector should be on the site at all times during construction (Reference 5).

3.5.1 Compaction

During compaction of each lift, compactive effort and uniformity of compaction should be observed and recorded. Compactive effort is estimated by the number of passes or equipment of a known size and weight that will achieve the design specifications for the fill material (Reference 5). The compaction effect, the testing program and the fill's engineering properties are established by the test fill program.

Design specifications usually require achievement of a minimum percentage of the maximum density at a specified range of water contents (i.e. ASTM methods D698 or 1557). The specified density/water content corresponds to the density/water content at which the minimum specified soil properties can be achieved. This density/water content is then tested during quality control of the backfilling (Reference 5).

Specific tests to ensure that compaction results correspond to design standards include field density tests (nuclear, sand-cone and others), field water content measurements, laboratory compaction tests, and both field and laboratory permeability tests. The methods and QC measures for conducting these tests may be found in several documents (References 2, 8, 9). The main tools used for controlling the quality of compaction are field density and water content measurements, with supplementary laboratory compaction tests to monitor changes in soil material. Presently, nuclear probes are often used to measure field density and water content because of ease and quickness of testing. However, nuclear devices must be calibrated for each soil that is to be tested. In addition, if nuclear devices are used, other field density and moisture content measurements, such as sand cones and oven drying, should be made periodically to confirm nuclear results. Again, it is necessary to measure density, moisture, and compactive effort in the field to ensure that the required density and hydraulic conductivity is achieved during compaction (Reference 5).

Minimum test frequency and test spacing should be specified for all tests in the test plan (Reference 5).

Thin-walled tube or block samples may be taken for laboratory hydraulic conductivity tests (ASTM D 1587; Reference 9), or field hydraulic conductivity tests may be performed using techniques such as a sealed double-ring infiltrometer. Several design engineers recommend that sealed water content/density measurements and thin-walled tube samples for laboratory hydraulic conductivity tests be obtained from the lift underlying the lift that has just been compacted. Following thin-walled tube sampling or nuclear density measurement, the resulting hole is filled with backfill material and hand-tamped or is grouped with bentonite (Reference 5).

Upon completion of the dike, QC personnel should check that it is rolled smooth to seal the surface so that precipitation and/or leachate can run freely to the leachate collection sump. The completed dike should be surveyed to ensure that thickness, slope, and surface topography are as required by the design specifications. Seals around objects penetrating the slope and dikes (e.g., leak detection system stand pipes) also should be checked for integrity (Reference 5).

3.5.2 Backfill Material Inspection

Inspection of the backfill material can be largely visual; however, QC personnel conducting this inspection must be experienced with visual-manual soil classification techniques (Reference 9; ASTM D 2488). Changes in color or texture may indicate a change in soil type or soil water content. The soil also may be inspected for roots, stumps, and large rocks. In addition, as a check of visual observations, samples of the soil usually are taken and tested to ensure that the soil's index properties are within the range stated in the specification. The number of index tests to be conducted depends on site-specific conditions (i.e., soil type and heterogeneity) and the experience of the QC personnel. Usually a minimum number of tests per cubic yard of material is specified, with additional tests required by the inspector if visual observations suggest a change in soil type (Reference 5).

When bentonite/soil mixtures are specified, incoming bentonite should be inspected to ensure that its quality is as specified. For all bentonite shipments, certification of compliance with material specification should be obtained from the manufacturer or supplier. In addition, the quality of the arriving bentonite should be tested frequently for dry fineness, pH, and viscosity and fluid loss of a slurry made from the bentonite. Dry fineness is the percentage passing a 200-mesh sieve. It is necessary to control dry fineness to ensure proper mixing of the bentonite (Reference 5). Slurry viscosity, slurry fluid loss, and pH are standard tests specified by the American Petroleum Institute (Reference 10).

3.6 References

1. *Code of Federal Regulations* Title 40, Parts 264 and 270, July 1, 1987.

2. U.S. Department of the Navy, May 1982, *Engineering Design Manual NAVFAC DM-7-1*, Naval Facilities Command, Washington, D.C.

3. Sowers G.F., 1979, *Soil Mechanics and Foundations: Geotechnical Engineering*, The MacMillan Company, New York.

4. Technical Manual: *Geotechnical Analysis for Review of Dike Stability (GARDS)* developed by R. M. McCandless, Dr. A. Bodoczi, and P. R. Cluxton of the University of Cincinnati, for the Hazardous Waste Engineering Laboratory, Office of Research and Development, U. S. Environmental Protection Agency; Cincinnati, Ohio 45268; EPA Contract No. 68-03-3183, Task 19, March 1986.

5. Draft Technical Resource Document: *Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities*; Hazardous Waste Engineering Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency; Cincinnati, Ohio 45268; EPA/530-SW-86-007, March 1986.

6 *Permit Applicant's Guidance Manual for Hazardous Waste Land Treatment, Storage and Disposal Facilities* (Volumes 1 and 2), Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency; Washington, D.C. 20460; SW-970, January 1984.

7. Technical Guidance Document: *Construction Quality Assurance for Hazardous Waste Land Disposal Facilities*; Hazardous Waste Engineering Research Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, Ohio 45268; EPA Contract No. 68-02-3952, Task 32; October 1986.

8. U.S. Department of the Army, 1970, *Laboratory Soils Testing* EM-1110-2-1906, Office of the Chief of Engineers, Washington, D.C.

9. ASTM, 1985, *The American Society for Testing and Materials 1985 Annual Book of ASTM Standards* Volume 4.08, "Soil and Rock; Building Stones," Philadelphia, Pennsylvania.

10. API 1982, American Petroleum Institute, *API Recommended Practice: Standard Procedure for Testing Drilling Fluids* API RP13B, American Petroleum Institute, Dallas, Texas

11. Boutwell, G.P. Jr., R. B. Adams, and D.A. Brown, 1980. Hazardous Waste Disposal in Louisiana. Geotechnical Aspects of Waste Disposal. American Society of Chemical Engineers, A Two Day Seminar.

12. *An Engineering Manual for the Evaluation of Stability of Dikes*, Permit Writer's Training Program, U.S. EPA, 1983.

13. *Groundwater*. Freeze and Cherry, Prentice-Hall, Englewood Cliffs, New Jersey, 1979.

14. Seed, H. Bolton, et. al., "Evaluation of Liquefaction Potential Using Field Performance Data"; In: *Journal of Geotechnical Engineering*; Vol 109, No. 3, March 1983.

15. Seed and Idriss; "Simplified Procedure for Evaluating Soil Liquefaction Potential"; In: *Journal of the Soil Mechanics and Foundations Division ASCE* Vol. 9, No. 7, September, 1971, p. 1,249-1,273.

16. Das, Braja M.; *Fundamentals of Soil Dynamics*; Elsevier Science Publishing Co., Inc., 1983.

the requirements for cover composition and configuration will be selected. Reference 1 provides technical guidance on the design process. Reference 2 describes a recommended 39-step approach to evaluating cover designs. The major design elements to consider will be discussed in the following section.

5.2.1 Site Characterization

Site characterization is of primary importance throughout the design process for a land disposal facility beginning with the initial siting of the facility. For cover design, site characterization directly impacts the criteria chosen for material selection and design to prevent erosion and to promote the establishment of hardy vegetation. The following discussion will introduce several key aspects of site characterization and their impacts on cover design.

5.2.1.1 Topography

Topography becomes a major factor in cover design when the landfill is sited in areas with hilly terrain or canyons and where surface impoundments may be below ground. In these environments, a considerable amount of surface water run-on should be expected, and the designer must be prepared to manage or prevent this surface run-on from traveling onto the cover. The designer should address the potential problem by performing the routine analyses of surface water flow for the surface water management requirements described in Chapter 6.0. It may be determined after analysis that traditional perimeter diversion systems will not be adequate and that other designs need to be considered. One option is to construct a central drainage system through the center of the landfill. For a flat site without natural positive drainage, the cover system must be designed to provide positive drainage of precipitation off the site to prevent ponding over the cover.

5.2.1.2 Precipitation

The intensity, duration, and frequency of storms must be determined to calculate the volume of surface water run-on or run-off that must be managed. The rate of infiltration (percolation) will directly impact the design of the drainage layer. An analysis of local precipitation patterns will also provide information on whether a potential for flooding exists. If there is flooding potential, the flood characteristics (e.g. stagnant backwater or scour potential due to flow) must be evaluated and measures designed to prevent damage to the cover or ponding on the cover. Local, site-specific precipitation data should be used whenever available for design calculations. Average annual precipitation maps developed by the U.S. Department of Agriculture and the National Weather Service are appropriate for use in review of designs. Section 2 of Reference 2 provides a more in-depth discussion of the review of precipitation data.

Precipitation data, particularly the annual distribution of rainfall, is also critical to the selection of the types of vegetation to be established on the cover. Since closure performance standards require that maintenance be minimized, vegetation should be selected that would adapt to the environment with a minimum amount of irrigation.

5.2.1.3 Other Climatological Data

In climates that experience freezing temperatures or drought, the upper surface layers of a land disposal unit cover may be damaged by the buckling or sliding of layers after thawing or by cracking during extended periods of drought. As a general rule, the geomembrane and the top of the low permeability soil layer, are the most susceptible to damage due to severe weather and should be placed below the depth of freezing or severe drying. Freezing also increases the amount of surface water run-off expected during winter months, as percolation through frozen ground is limited. This fact should be considered in run-off discharge calculations for drainage channel design. Freezing indexes illustrated as map contours have been developed by the U.S. Weather Bureau. Indices showing the severe drought regions of the country are available from regional Soil Conservation Service offices. As was true for precipitation data, the more site-specific data available, the more accurate the design calculations. Reference 1 discusses the influence climatology has on cover design in Section 3. Reference 2 addresses the review of climatological data in Section 3.

5.2.1.4 Soils

An assessment of the properties of the in-situ soils, while not a constraint in the design of the cover system, is important from a cost-effectiveness standpoint. Considerable savings could be gained if site material can be used as part of the intermediate or final cover system. Soil tests run under the direction of a qualified geotechnical engineer for land disposal unit siting and design are useful sources of information during the material selection process. A more detailed discussion of soil properties is provided in Section 5.3, Materials, of this chapter.

5.2.1.5 HELP Model

To assist the designer in determining the influence that site characterization factors will have on the performance of a cover system design, a computer model was developed called Hydrologic Evaluation of Landfill Performance (HELP). The HELP Model was designed by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) for the U.S. EPA Municipal Environmental Research Laboratory. The Model is generally accepted for designing landfill cover layer systems and for comparing alternative cover and total landfill configuration designs. (Reference 3, Section 1). Use of the Model in design of leachate collection systems is discussed in Chapter 4.0.

The HELP program calculates daily, average and peak estimates of water movement across, into, through, and out of landfills. The input parameters for the model include soil properties, precipitation and other climatological data, vegetation type, and landfill design information. Default climatologic and soil data are available but should be verified as reasonable to expect in the particular site setting. Outputs from the model include precipitation, runoff, percolation through the base of each cover layer subprofile, evapotranspiration, and lateral drainage from each profile. The Model also calculates the maximum head on the barrier soil layer of each subprofile and the maximum and minimum soil moisture content of the evaporative zone. Data from the model are presented in a tabular report format and include the input parameters used and a summary of the simulation results. Results are presented in several tables of daily, monthly and annual totals for each year specified. A summary of the outputs is also produced, which includes average monthly totals, average annual totals and peak daily values for various simulation variables. (Reference 3, Sections 4 and 5)

Use of the HELP model should not be attempted without reading the User's Guide, Reference 3, or the Model Documentation, Reference 4, both prepared by the designers of the program.

5.2.2 *Waste Characterization*

Cover settlement has been determined to be caused by primary consolidation and secondary compression of the waste mass, underlying natural soils, and from collapse of voids or cavities in the fill and around containers. Primary consolidation occurs when the void ratio of a soil or waste is decreased due to the expulsion of fluids from the voids under excess hydrostatic pore pressure. Secondary compression occurs by deformation of the skeletal structure of the mass and compression of gases in the voids. The collapse of voids or cavities is due to corrosion, oxidation, combustion, or biochemical decay of the landfilled materials. The designer should be aware of the distribution of void spaces and other physical conditions of the waste at the time of burial, the waste placement operations (e.g. lift thickness, compactive effort, etc.) and the chemically-related changes due to the composition of the wastes that may take place over a long period (Reference 1, p. 9, Reference 5, p. 2).

Wastes which enter the land disposal unit are either disposed of in bulk or in containers. Bulk wastes may exhibit the settlement characteristics of soils in that they continue to consolidate over time, but at a steadily decreasing rate depending upon the physical characteristics of the waste and the methods of waste placement. To assist in the settlement analysis, recent efforts have been made to determine the engineering properties of several types of wastes through laboratory testing. Results of these efforts are presented in Reference 5 in Section 2. The laboratory analyses, however, should never be used as more than a general guide to expected properties. The wastes reported to have been disposed of at a given facility should be evaluated to the extent possible for a site-specific determination.

Containerized wastes do not behave as predictably as bulk wastes. Consolidation of drummed wastes occurs at a considerable period of time after waste placement when drum deterioration occurs. An acceptable, accurate analytical method is not currently available for prediction of the time and extent of this later settlement due to container deterioration. However, the designer should address the potential for future subsidence due to the disposal of containers and qualitatively approximate the potential damage.

Another important characteristic of land disposal unit wastes which directly effects settlement is the percent of void space within the cell configuration of wastes. An estimate of the effects these void spaces will have on long term settlement is required. Often, sufficient attention is not given to filling the void spaces between containers within landfill cell lifts. When the lifts have not been properly backfilled, void spaces several rows deep may be left as channels for the downward migration, or piping, of backfill. Backfill piping can cause differential settlement and damage to the cover.

The chemical composition of the wastes must be carefully reviewed to determine gas generation potential. Diversions and vents may be required in the design to provide a release pathway for gases blocked by the cover from upward migration. If low concentrations of toxic components are expected, vents directly to the atmosphere may be adequate for dispersion in the air at acceptable levels. It may be necessary to provide on-line or contingency features for absorption filters or other means of reducing concentration of toxic components if the potential exists for the gas or volatile component to reach harmful concentrations (Reference 1, p. 13). Gases evolve from the decay or biodegradation of buried organic matter; thus, gas control (venting) is principally a concern at municipal waste, not hazardous waste, landfills.

5.2.3 *Settlement/Subsidence*

A potential threat to the integrity of the cover is uneven settlement of the wastes and fill that comprise the foundation of the cover. Recent guidance (Reference 5) has been published regarding the prediction/mitigation of subsidence damage to covers and will be briefly summarized in the following paragraphs.

Long-term settlement of hazardous waste land disposal units should be analyzed on the basis of the deformation of the waste layers and the deterioration of the waste containers. Settlement due to deformation of the waste layers is most likely to occur after closure of the land disposal unit and final placement of the cover. Therefore, this type of settlement has more potential to cause subsidence damage to the cover than consolidation settlement, much of which can occur or can be made to occur prior to closure. (Reference 5, p. 19)

Several models have been developed to analyze the process of differential settlement. Most equate the layered cover to a beam or column undergoing deflection due to various loading conditions. While these models are useful to designers in understanding the qualitative relationship between various land disposal unit characteristics and in identifying the constraining factors, accurate quantitative analytical methods have not been developed (Reference 5, Section 4).

If settlement is anticipated, several design options are available. For example, the cover thickness can be designed such that after displacement occurs, drainage of run-off is still adequate. Exhibit 5-2 illustrates this design compensation method. Another option is to increase the side slopes of the cover. (Reference 5, p. 71).

In summary, although settlement has the potential to seriously damage a land disposal unit cover, the analytical methods available to estimate the effects are still inexact and require additional experimentation and field observation. For now, the designer of land disposal unit covers should determine whether the potential for settlement exists due to the type of wastes and landfilling procedures used and design the cover to provide a tolerance for settlement effects (Reference 5, Section 5).

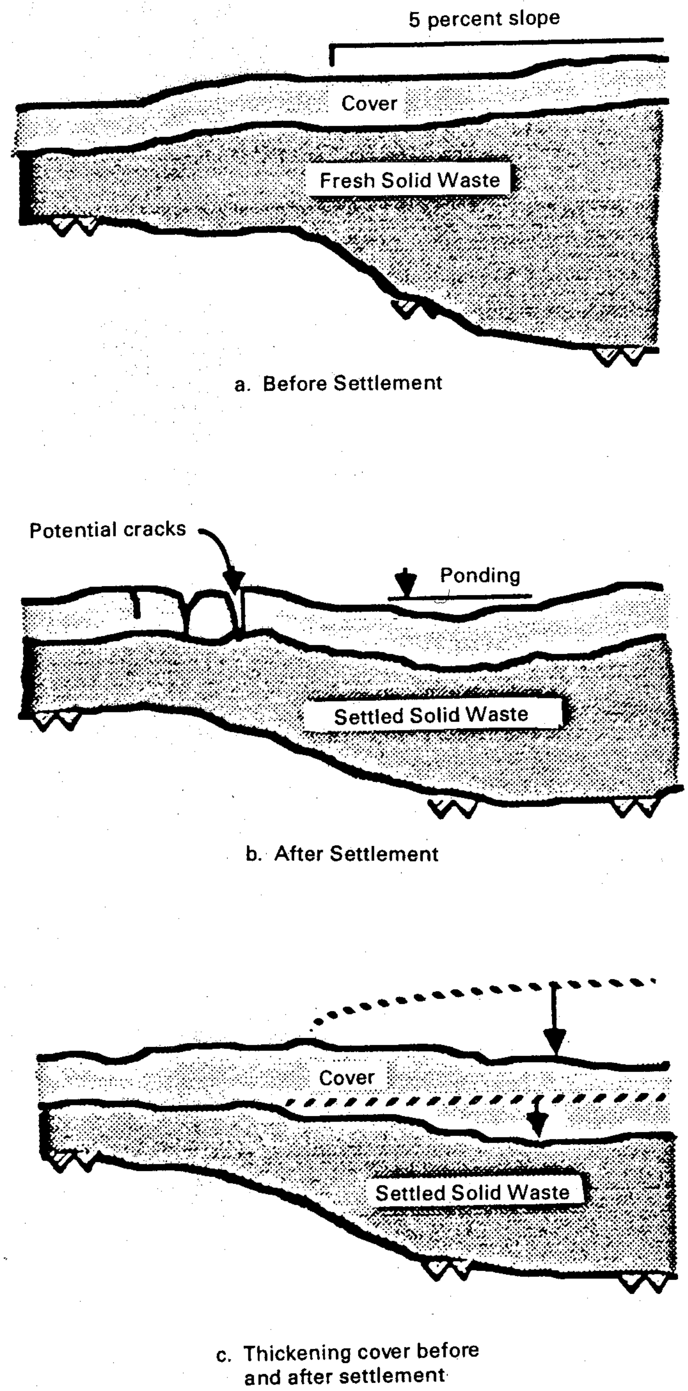
5.2.4 *Slope Stability*

One threat to the continued soundness of the cover is displacement due to the slope instability. Slope stability analyses should be performed to assess the potential for slope failure by various failure modes (e.g., rotational, sliding, wedge), as appropriate, based upon the slope configuration. To adequately perform the stability analyses, the strength properties of the cover system components, the waste, and the foundation soils must be known along with seepage conditions. A detailed discussion of slope stability can be found in Chapter 3 of this document.

5.2.5 *Erosion Potential*

In addition to ensuring embankment slope stability, the designer should design the cover to minimize soil erosion. To assist the designer in predicting erosion potential of various design options, EPA recommends use of an empirical formula called the Universal Soil Loss Equation (USLE) which is used to calculate the average annual soil loss. The average annual soil loss is predicted based upon a number of factors including the geographical location, the length and steepness of slopes, the texture of the cover soil, and the vegetation established.

Exhibit 5-2. Thickened Cover for Tolerance of Settlement



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