1C- FOUNDATIONS UNIT

Publication No. FHWA-SA-96-038

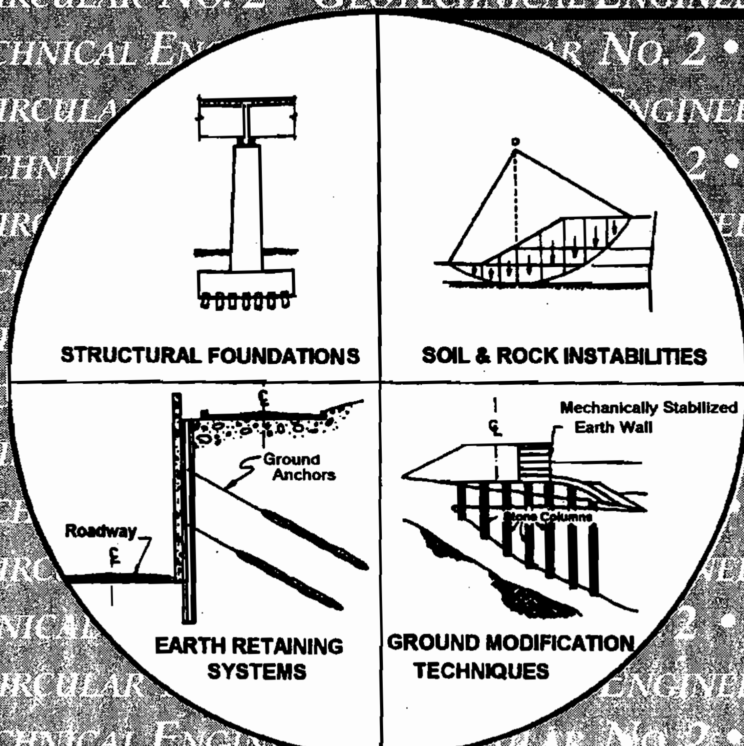
U.S. Department of Transportation
Federal Highway Administration

FEBRUARY 1997

OFFICE OF ENGINEERING
OFFICE OF TECHNOLOGY APPLICATIONS
400 SEVENTH STREET, SW
WASHINGTON, DC 20590

GEOTECHNICAL ENGINEERING CIRCULAR NO. 2

EARTH RETAINING SYSTEMS



TECHNOLOGY APPLICATIONS

Innovation Through Partnerships

DISCLAIMER

The information in this document has been funded wholly or in part by the U.S. Department of Transportation, Federal Highway Administration (FHWA), under Contract No. DTFH61-94-C-00099 to GeoSyntec Consultants. The document has been subjected to peer and administrative review by FHWA, and it has been approved for publication as a FHWA document.

In this document, several commercially-available earth retaining systems have been identified by trade name. Also, photographs of several of these systems have been included in the document to illustrate earth retaining system construction. Commercially-available systems which are not identified in this document may be equally viable to those which are identified. The mention of any trade name or photograph of a particular system does not constitute endorsement or recommendation for use by either the authors or FHWA.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Mr. Jerry A. DiMaggio and Mr. Chien-Tan Chang of U.S. Department of Transportation (USDOT) Federal Highway Administration (FHWA) who provided significant technical assistance and review during preparation of the document. Also, Professor J.K. Mitchell of Virginia Polytechnic Institute and State University reviewed the document and provided many valuable suggestions. The authors would also like to thank the following individuals who reviewed the document and served on the Technical Working Group for this project:

- Rich Barrows - FHWA;
- Richard Cheney - FHWA;
- James Lyons - FHWA;
- Mark McClelland - Texas Department of Transportation;
- Andy Munoz - FHWA;
- Blake Nelson - Minnesota Department of Transportation;
- Bruce Pfister - Wisconsin Department of Transportation; and
- Tom Saad - FHWA.

The authors would also like to acknowledge the following firms and agencies that provided photographs of earth retaining systems and product information:

- Criblock Retaining Walls Inc.;
- Contech Construction Products Inc.;
- Doublewal Corporation;
- FHWA;
- KB Technologies Ltd.;
- Maccaferri Gabions Inc.;
- Nicholson Construction Company;
- Reinforced Earth;
- Schnabel Foundation Company;
- U.S. Department of Agriculture Forest Service;
- Tensar Earth Technologies, Inc.; and
- VSL Corporation.

Finally, the authors would like to thank Mrs. Ann Taylor of GeoSyntec Consultants who drafted many of the figures and assisted in the layout of the document.

PREFACE

Temporary and permanent earth retaining systems are often used on highway projects for grade separation, bridge abutments, slope stabilization, and excavation support. Prior to 1970, earth retaining systems used for highway consisted primarily of rigid gravity and semi-gravity concrete gravity walls. During the past 25 years, however, numerous alternative earth retaining systems have been introduced into the United States marketplace. These alternative systems are undergoing continuing modifications as a result of advances in analysis techniques, interpretation of field performance data, and construction methods, materials, and equipment. Owing to the large number of available earth retaining systems, selection of a specific system for use on a project may not be straightforward as several systems may be technically viable, practical to construct, and cost-effective.

This document has been written to provide up-to-date information on earth retaining systems currently being constructed in the United States for highway applications. Earth retaining systems discussed in this document include:

- rigid gravity and semi-gravity walls;
- prefabricated modular gravity walls;
- mechanically stabilized earth (MSE) walls;
- reinforced soil slopes;
- non gravity cantilevered walls and anchored walls including sheet-pile walls, soldier pile and lagging walls, slurry (diaphragm) walls, tangent pile and secant pile walls, and soil mixed walls; and
- in-situ reinforced walls such as soil-nailed walls and micropile walls.

This document is a synthesis of practical information on construction, selection, contracting practices, and inspection for these earth retaining systems. A description of detailed design of these systems is beyond the scope of this document, however, a list of references that include information on state-of-the-practice design methods for earth retaining systems is provided.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

Figure | Page

Figure | Page

CHAPTER 1

INTRODUCTION

1.1 PURPOSE

The purpose of this document is to present a broadly-scoped primer and resource document on temporary and permanent earth retaining systems for use on highway projects. The intended audience includes geotechnical, structural, and highway design and construction specialists involved with the selection, design, contracting, and construction of these systems. Issues related to earth retaining system selection, appropriate contracting practices, and construction monitoring are discussed in detail in this document. This document also presents general information on system design/analysis procedures and identifies references where detailed design/analysis information can be obtained.

Once the necessity for an earth retaining system has been identified for a particular highway project, this document can be used to identify wall system alternatives and their key features. Information in this document is presented within a framework designed to enable the reader to systematically evaluate and select specific wall systems for a particular project application based on technical, physical, and economic factors. During project implementation, the reader can use this document to obtain information on wall system design requirements, construction detailing, contracting practices, and construction monitoring and inspection.

1.2 BACKGROUND

Prior to 1970, earth retaining systems for highway applications were predominantly of concrete gravity and semi-gravity construction (Cheney, 1990). If excavation support was required, internally braced excavation procedures were employed. Design methodologies, performance characteristics, construction methods, and contracting procedures were, and continue to be, relatively well-established for these wall systems.

Since the early 1970s, numerous alternative wall systems have been introduced into the U.S. marketplace. Many of these newer systems have application to highway projects. Examples include mechanically stabilized earth (MSE) walls and reinforced soil slopes (RSS) employing metallic or polymeric internal reinforcement; anchored walls, such as soldier pile and lagging walls, slurry (diaphragm) walls, tangent pile walls, secant pile walls, and soil mixed walls; prefabricated modular gravity wall systems including cribs, bins, and gabions; and in-situ reinforced wall systems such as soil-nailed walls and micropile walls. O'Rourke and Jones (1990) provide an overview relating to the changes and developments in earth retaining system materials, design, and construction for the period 1970-1990. They discuss the increased necessity for excavation support due to the growth in urban underground construction, advances in construction materials and equipment for anchored wall systems, advances in the manufacturing of polymeric materials for MSE wall reinforcement, and the use of soil nailing as a viable means of excavation support.

During the 25-year period since 1970, the development and project application of these earth retaining systems has grown at a rate that makes it difficult to keep abreast of the changes. These changes have led to significant cost savings for many highway construction projects, but occasionally, design and construction-related problems have resulted from inadequate knowledge of the characteristics of the new system. Problems have included misapplication of wall systems, use of inadequate materials or design details, inadequate specifications, lack of specifications enforcement, inequitable bidding procedures, and inconsistent selection, review, and acceptance procedures (Federal Highway Administration (FHWA), 1988). Furthermore, during the period of 1970-1990, a variety of earth retaining system contracting procedures have evolved. In addition to traditional contracting methods, methods involving material-supplier developed designs, specialty contractor design/build specifications, and performance-based specifications have found widespread use. As a result of the rapid rate of evolution of earth retaining system technology and contracting procedures, an information gap sometimes exists amongst highway professionals regarding the selection, design, contracting, and construction of these wall systems. This document is intended, in part, to address this information gap.

A number of earth retaining systems introduced in the past 25 years were originally protected from general use by patent or trademark. These proprietary systems included patented features such as wall components, methods of construction, and specialized construction equipment. Presently, most patents for complete earth retaining systems have expired; however, several commercially-available systems still contain proprietary features. As a result of technical innovation and a trend toward proprietary components, a wide variety of earth retaining systems is now available for use on highway projects. These systems have been actively marketed by system developers, manufacturers, suppliers, and specialty contractors. Available literature on these systems tends to highlight the system advantages, making it difficult to understand the technical limitations, cost effectiveness, and recommended applications of each system and to distinguish between similar systems. This document presents information that will enable the user to better understand similarities and differences between various commercially-available systems.

1.3 RELEVANT PUBLICATIONS

A number of manuals describing selection, design, contracting, and construction of specific earth retaining systems are available to the interested reader. These manuals have typically emphasized analysis and design aspects of earth retaining systems. This document has been developed utilizing information from these and other manuals and publications. It should be noted that many manuals on earth retaining system design contain conflicting specific guidance, particularly for more recently developed systems. It is not the intent of this document to resolve such conflicting information, but instead to present information on design concepts for categories of earth retaining systems. This information is presented for purposes of earth retaining system selection and preliminary design. Several of the manuals used in the development of this document are listed below along with a brief description of the pertinent contents.

- "American Association of State Highway and Transportation Officials (AASHTO) - Standard Specifications for Highway Bridges, Sixteenth Edition, 1994"

  This manual presents design and construction related specifications and commentary for ordinary highway bridges. Sections of this manual (Division I - Section 5; Division II -Section 7) address the design and construction of earth retaining systems for bridge applications. General design and construction related specifications are described for conventional gravity and semi-gravity walls, MSE walls, non-gravity cantilevered walls including anchored walls, and prefabricated modular gravity walls.

- "Naval Facilities Engineering Command (NAVFAC) DM7.02, Foundations and Earth Structures, Department of the Navy, 1986"

  This manual contains general design and analysis procedures for conventional gravity and semi-gravity walls, non-gravity cantilevered walls including sheet-pile walls and soldier pile and lagging walls, and anchored walls. Methods for computing earth pressures for design are also described.

- "National Cooperative Highway Research Program (NCHRP) Report 343, Manual for the Design of Bridge Foundations, Transportation Research Board, National Research Council, 1991"

  This manual contains general design and analysis procedures for conventional gravity and semi-gravity retaining walls and abutments. Design and analysis procedures are also included for shallow foundations, driven piles, and drilled shafts. Methods of estimating movements and load factor design specifications are also provided.

- "U.S. Department of Transportation, Federal Highway Administration, Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Design and Construction Guidelines, FHWA-SA-96-071, 1996"

  This manual contains guidelines for the analysis and design of MSE walls and reinforced soil slopes. Also included are descriptions of construction procedures, construction inspection and performance monitoring, and contract specifications for these systems.

- "U.S. Department of Transportation, Federal Highway Administration, Permanent Ground Anchors, FHWA-DP-68-1R, 1988"

  This manual contains guidelines for the analysis and design of anchored walls. Also included is information on ground anchor applications, corrosion of ground anchors, load testing of ground anchors, and construction inspection.

- "U.S. Department of Transportation, Federal Highway Administration, Manual for Design and Construction Monitoring of Soil-Nailed Walls, FHWA-SA-96-069, 1996"

  This manual presents information on design and analysis for soil-nailed walls. Also included is information on appropriate applications of soil-nailed walls, construction procedures, performance monitoring, and the use of shotcrete for wall facings.

The proceedings from the 1990 American Society of Civil Engineers (ASCE) conference on *"Design and Performance of Earth Retaining Structures"* (ASCE Geotechnical Special Publication No. 25, 1990) is a valuable resource in that the papers in the proceedings trace the emergence, development, and application of many different types of wall systems during the period of 1970 to 1990. The series of papers in the proceedings also contains detailed information on selection, design, construction, and contracting practices for many of the wall systems described in this document.

1.4 EARTH RETAINING SYSTEM CLASSIFICATION

The purpose of an earth retaining system is to stabilize an otherwise unstable soil mass by means of lateral support or reinforcement. For highway applications, wall systems are used for grade separations, bridge abutments, slope stabilization, and excavation support (figure 1). Many of the available wall systems are capable of providing adequate lateral support for some or all of the applications shown in figure 1. Most systems are, however, designed to work best and prove to be most economical or efficient for only a limited range of earth retaining system applications. Therefore, it is useful to classify common wall systems based on the factors that will govern their selection and use.

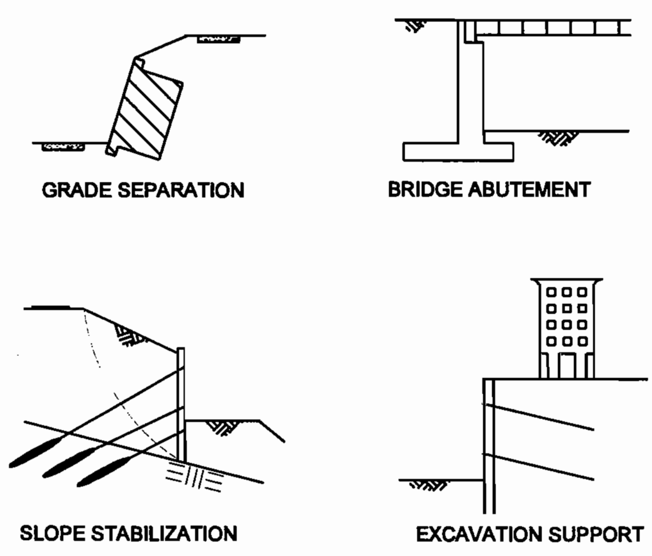


Figure 1. Applications of earth retaining systems.

A classification system for earth retaining systems is presented in figure 2. This classification system represents a modification to a previous classification system developed by O'Rourke and Jones (1990). In figure 2, earth retaining systems are classified according to construction method (i.e., fill construction or cut construction) and basic mechanisms of lateral load support (i.e., externally stabilized or internally stabilized). Fill wall construction refers to a wall system in which the wall is constructed from the base of the wall to the top (i.e., "bottom-up" construction). Cut wall construction refers to a wall system in which the wall is constructed from the top of the wall to the base (i.e., "top-down" construction). It is important to recognize that the "cut" and "fill" designations refer to how the wall is constructed, not necessarily the nature of the earthwork (i.e., cut or fill) associated with the project. For example, a fill wall, such as a prefabricated modular gravity wall, may be used to retain earth for a major highway cut. Externally stabilized wall systems utilize an external structural wall, against which stabilizing forces are mobilized. Internally stabilized wall systems employ reinforcement which extends within and beyond the potential failure mass. Using figure 2, each wall system is given a two-part classification. For example, a sheet-pile wall is classified as an "externally stabilized cut wall system" whereas a mechanically stabilized earth (MSE) wall is classified as an "internally stabilized fill wall system".

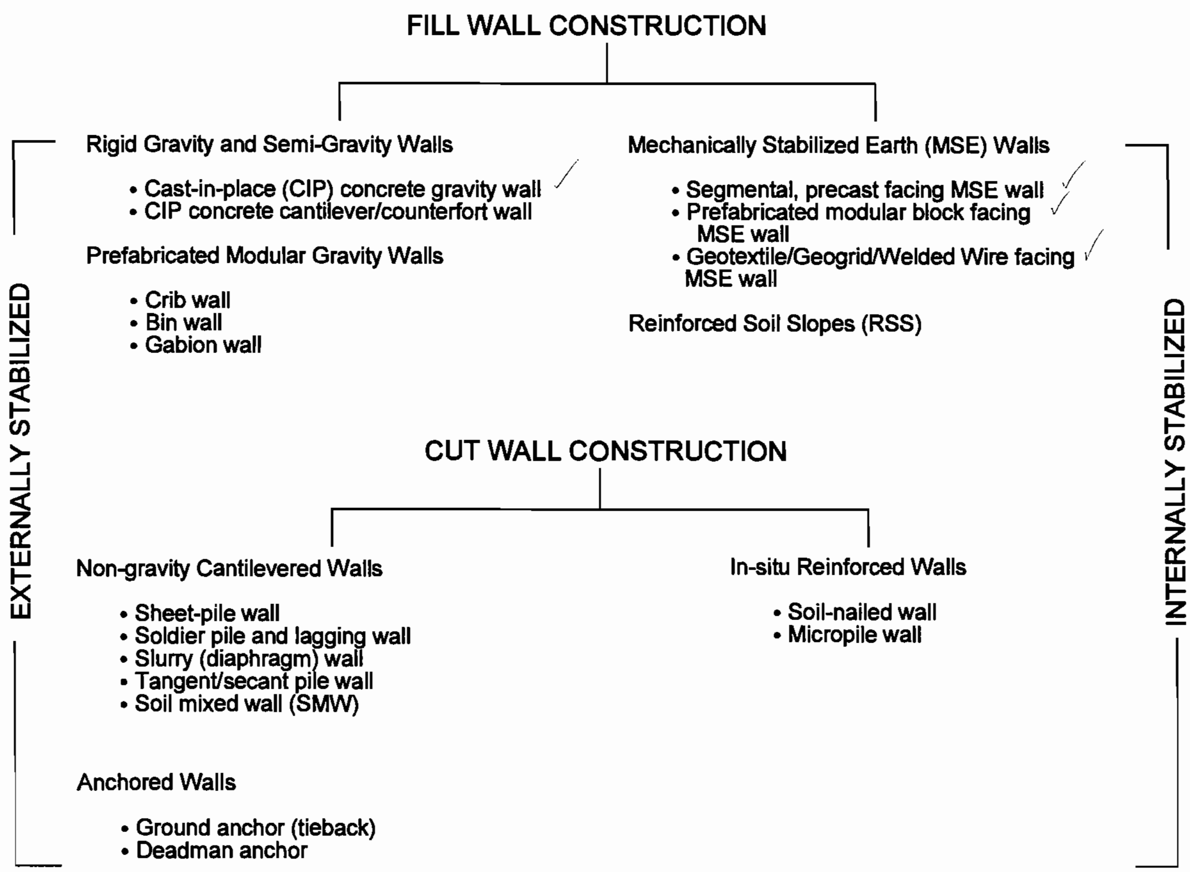


Figure 2. Earth retaining system classification.

Each earth retaining system presented in this document can be assigned to one of the categories listed below.

- Rigid Gravity and Semi-Gravity Walls: these walls derive their capacity through a combination of the dead weight of the wall and structural resistance.

- Prefabricated Modular Gravity Walls: these walls employ interlocking soil-filled or rock-filled concrete, timber, or steel modules that resist lateral load by acting as a gravity wall.

- Mechanically Stabilized Earth (MSE) Walls: these walls employ either metallic (strip, grid, or wire mesh) or polymer (strip, grid, or sheet) reinforcement in the backfill soil that resists lateral load through interface shear and passive resistance between the soil and the reinforcement. The reinforcement is connected to a vertical or near-vertical facing.

- Reinforced Soil Slopes (RSS): these systems employ tensile reinforcement in the backfill soil in a manner similar to MSE walls. The inclination of the slope face is typically less than 70 degrees. The reinforcement extends to the slope face and is connected to a facing, where present.

- Non-gravity Cantilevered Walls: these walls derive resistance through shear and bending stiffness and embedment of vertical structural elements.

- Anchored Walls: these walls derive resistance similarly to a non-gravity cantilevered wall, but, substantial additional support is obtained through the use of anchors. Anchors may be prestressed tiebacks (ground anchors) which extend from the wall face back to a grouted zone or deadman anchors which extend from the wall face back to a mechanical anchorage such as a steel sheet-pile or concrete block.

- In-situ Reinforced Walls: these walls employ metallic bars that are drilled and grouted, or driven into the retained soil mass to develop lateral resistance at each level.

The earth retaining systems shown in figure 2 are technically feasible for both temporary and permanent applications. In most cases, however, certain systems may not be cost-effective for temporary applications. Compared to permanent walls, walls used for temporary applications generally have less restrictive requirements on material durability, design factors of safety, performance, and overall appearance. Also, walls that can be constructed rapidly are often used for temporary applications. For example, MSE walls with segmental, precast facings are not typically used for temporary applications since the cost of the facing components and the select backfill may be more than 50 percent of the total wall cost. More information on the use of wall systems for temporary and permanent applications is presented in chapters 2 and 4.

1.5 DOCUMENT ORGANIZATION

This document is concerned with the process of selection, preliminary design, construction of, and contracting practices for, currently available temporary and permanent earth retaining systems. The overall goal of this document is to present information to enable highway design and construction specialists to evaluate alternative wall systems and ultimately select an appropriate wall system(s) for a project application. To assist the reader in understanding the sequence of events for any wall system project, the flowchart in figure 3 was developed. The flowchart outlines the typical tasks involved in a wall system project and the responsible party for each task. The flowchart also indicates where information on each specific task can be found in this document. The organization of the remainder of this document is as follows:

- A two-page description of each wall system, termed an Earth Retaining System (ERS) Summary is presented in chapter 2. Each ERS Summary provides general information on a specific wall system and specific selection-based issues pertinent to the particular system.

- Construction methods, equipment, and materials for fill and cut wall construction are presented in chapter 3. Technical issues associated with the construction of wall systems for particular project applications are also discussed.

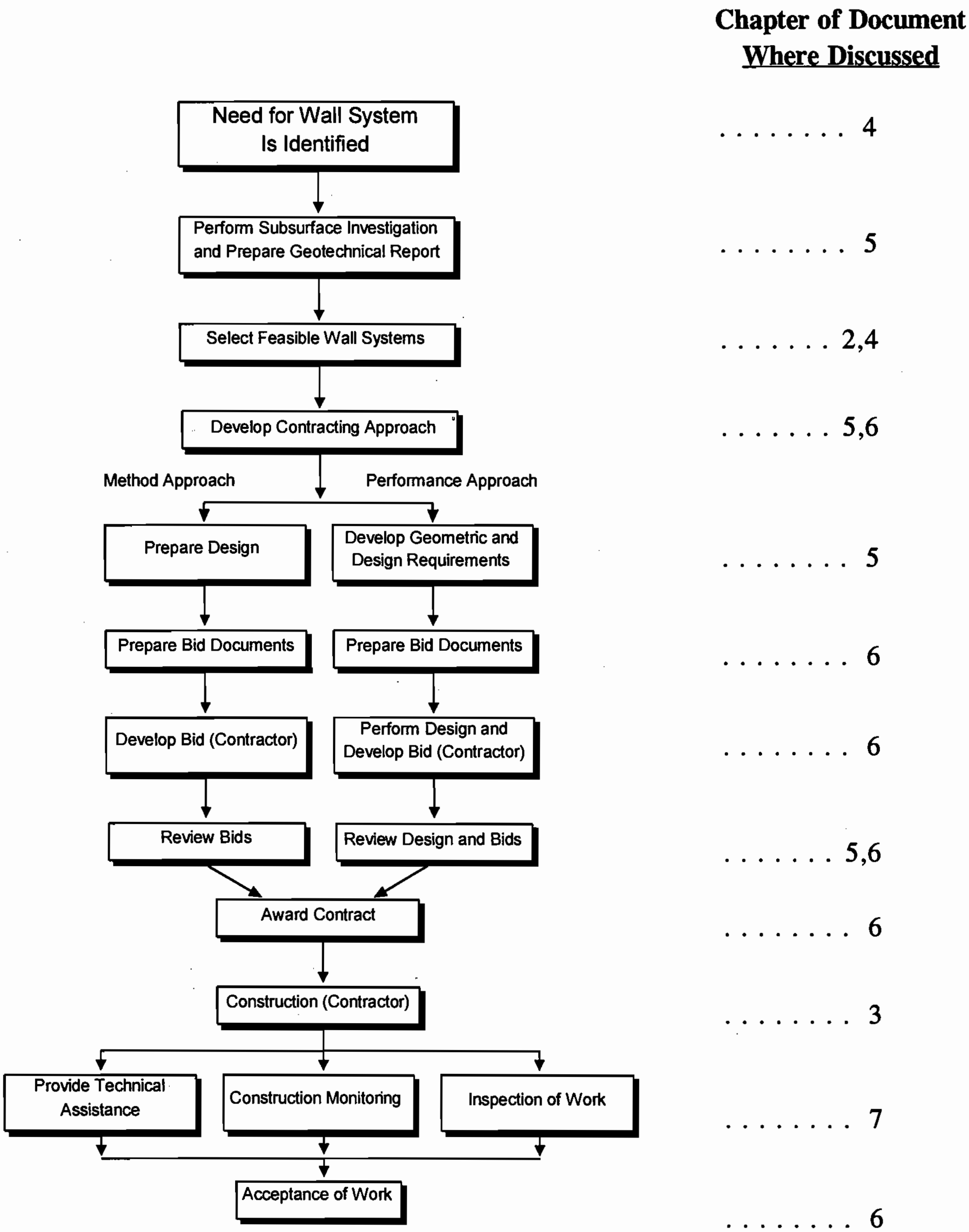
- A systematic approach for evaluating the applicability of a wall system to a specific project is detailed in chapter 4. A system selection flowchart and selection tables for both fill and cut walls are developed and their use is illustrated through two examples.

- An overview of analysis techniques and design concepts for earth retaining systems is presented in chapter 5. References to publications addressing detailed analysis and design are provided.

- Available options for contracting earth retaining system design and construction, including owner design and design-build are presented in chapter 6. Method-based and performance-based specifications are defined and the applicability of these types of specifications for the contracting of specific wall systems is described.

- Construction inspection and monitoring as it pertains to construction contract acceptance, construction materials, the execution of construction, and wall system performance is discussed in chapter 7.

The organization within each chapter of this document is based on the earth retaining system classification chart shown in figure 2. Throughout this document, information on construction, selection, design, and contracting approaches are presented for these wall systems, but the relationships between these components for a particular wall system project are not discussed in detail.



Note: Each task is the responsibility of the Owner, unless otherwise noted.

Figure 3. Wall system project tasks.

CHAPTER 2

TYPES OF EARTH RETAINING SYSTEMS

2.1 INTRODUCTION

The purpose of this chapter is to provide a quick reference to, and summary information on, a variety of earth retaining systems (ERSs). This goal is accomplished through use of a two-page ERS Summary for each wall system. Table 1 provides a list of the 17 wall systems for which ERS Summaries have been developed. The classification of each wall system is also presented in table 1.

Table 1. List of ERS summaries.

ERS Summary No.	Wall Type	Wall Classification
1	CIP concrete gravity wall	externally stabilized fill wall
2	CIP concrete cantilever wall	externally stabilized fill wall
3	crib wall	externally stabilized fill wall
4	bin wall	externally stabilized fill wall
5	gabion wall	externally stabilized fill wall
6	segmental, precast facing MSE wall	internally stabilized fill wall
7	prefabricated modular block facing MSE wall	internally stabilized fill wall
8	geotextile/geogrid/welded wire facing MSE wall	internally stabilized fill wall
9	reinforced soil slope (RSS)	internally stabilized fill wall
10	sheet-pile wall	externally stabilized cut wall
11	soldier pile and lagging wall	externally stabilized cut wall
12	slurry (diaphragm) wall	externally stabilized cut wall
13	tangent pile/secant pile wall	externally stabilized cut wall
14	soil mixed wall (SMW)	externally stabilized cut wall
15	anchored wall	externally stabilized cut wall
16	soil-nailed wall	internally stabilized cut wall
17	micropile wall	internally stabilized cut wall

The organization of each ERS Summary is described below. For easy reference, each ERS Summary has been prepared as a "stand-alone" two-page table.

2.2 WALL SYSTEM

Each ERS Summary begins with a list that includes: (1) the name of the wall system; (2) the category of the wall system; and (3) the classification of the wall system as defined using figure 2.

2.3 DESCRIPTION OF WALL SYSTEM

A standardized format is used in each ERS Summary to present information relating to selection, design, and construction of the considered earth retaining system. The format is subdivided into categories that are delineated in the ERS Summary by section headings. Section headings are listed below along with a commentary on the purpose of each section.

- Description

  In this section, the physical appearance and constituent materials of the wall system are described. Conceptual design procedures, load transfer mechanisms, and construction-related issues are also noted.

- General

  In this section, the following information is summarized: (1) typical applications; (2) special applications, if applicable; (3) unit cost range; (4) items included in the unit cost; (5) size requirements; (6) typical height range; and (7) commercially-available systems, if applicable.

  The reported unit cost ranges (presented in 1995 U.S. dollars) are approximate as actual costs will depend on wall height and costs of labor, materials, and equipment, which are dependent on the actual site location and other project-specific factors. For each ERS Summary, the cost range reported corresponds only to the height range reported. Unit costs for high walls and permanent walls are on the upper end of the range of unit costs reported in the ERS Summaries. These cost ranges can be used for comparisons of the relative costs of different wall systems. Cost estimates for wall systems should be developed based on project-specific information.

  Size requirements refer to the base width of the wall system required to ensure a satisfactory design for a particular wall system. It is convenient to report this as a function of wall height because as the height of a wall increases, the base width must also increase to ensure that the wall remains stable.

- Advantages and Disadvantages

  General advantages and disadvantages associated with each wall system are listed in each ERS Summary. Advantages or disadvantages relate to such factors as cost and availability of materials, labor, and equipment, relative ease of wall system construction, aesthetics of the wall system, performance characteristics, maintenance requirements, applicable site and soil conditions, and geometric requirements. For example, an advantage of a slurry (diaphragm) wall is that it can be constructed in varying soil conditions, while a disadvantage of a sheet-pile wall is that it is difficult to construct in gravelly soils.

- Primary System Components

  The major structural and geotechnical components of a particular wall system are identified in this section.

  A primary component of all fill walls is the backfill soil. Ideally, granular soil should be used for backfill since it is free-draining. For simplicity, "granular soil backfill" is presented as a primary system component for each of the fill walls described in the ERS Summaries. Clayey soils, however, which have relatively poor drainage characteristics, may be used as backfill for certain wall applications. The use of clayey backfill is discussed further in section 5.4.2.2.

  A primary component of most earth retaining systems is a drainage system. A properly constructed and maintained drainage system will minimize potential for poor wall performance resulting from the effects of surface-water infiltration and runoff and high ground water. For the ERS Summaries, "drainage system(s)" are presented as a primary component for all fill walls and several cut walls. Wall systems such as slurry (diaphragm) walls, tangent and secant pile walls, and soil mixed walls are most cost-effective when used for applications in areas where ground water exists at an elevation significantly higher than that of the base of the excavation. These walls can be designed to resist significant water loads such as those associated with a high ground-water table and, as such, drainage systems are not incorporated into the wall system design. Several types of drainage systems for fill and cut wall systems are illustrated and discussed in section 5.5.3.

- Additional Comments

  Additional items which relate specifically to the wall system are noted in this section. These items relate to construction techniques, construction monitoring, specific design and analysis considerations, and other aspects of the particular wall system.

Since the reader may be unfamiliar with some of the identified wall systems, figures and photographs are provided in each ERS Summary.

ERS SUMMARY NO. 1: Cast-in-place (CIP) Concrete Gravity Wall

Category of Wall: Rigid Gravity Wall
Classification of Wall: Externally Stabilized Fill Wall

Description

A CIP concrete gravity wall is generally trapezoidal in shape and constructed of mass concrete. The wall relies on self-weight to resist overturning and sliding due to the lateral stresses of the retained soil. Design procedures are well established for overturning and sliding analyses, and for evaluation of the bearing capacity of the underlying foundation soils. Backfill soil should be free draining to prevent water pressure from acting on the back of the wall.

General

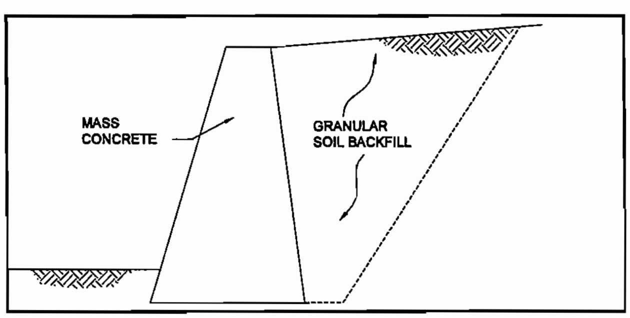
Typical applications:	Retaining walls
Unit cost range:	\$270-\$370 per square meter of wall face
Unit cost includes:	Concrete, granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Base width ranges from 0.5 to 0.7 of the wall height
Typical height range:	1-3 m

Advantages

- Conventional wall system with well-established design procedures and performance characteristics.
- Concrete is very durable in many environments.
- Concrete can be formed, textured, and colored to meet aesthetic requirements.
- Wall system is economical for wall heights less than 3 m.

Disadvantages

- Wall system requires a relatively long construction period because formwork must be erected and concrete must be poured and allowed to cure before backfill loads can be applied to the wall.
- Wall system cost will significantly increase if adequate source of select backfill is not available near project site.
- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- Deep foundation support, which increases wall system cost and construction time significantly, may be required if wall is founded on weak or



marginal soils.
- Wall system is rigid and is sensitive to total and differential settlement.
- Wall system is typically not cost-effective for temporary applications.

Primary System Components
- Mass concrete, generally without steel reinforcement
- Granular soil backfill
- Drainage system(s)

Additional Comments
- Batching, placement, and curing times of concrete should be monitored.
- Foundations should be adequately compacted before concrete is placed.

ERS SUMMARY NO. 2: Cast-in-place (CIP) Concrete Cantilever/Counterfort Wall

Category of Wall: Semi-gravity Wall
System Classification: Externally Stabilized Fill Wall

Description

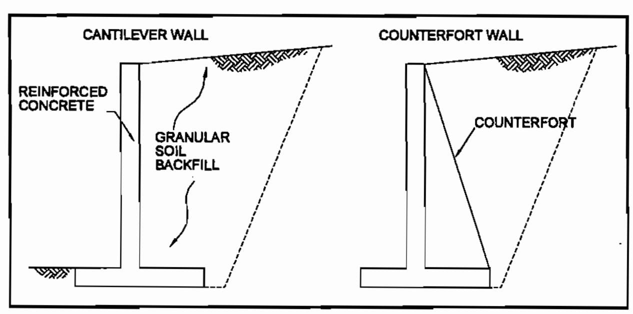
A CIP concrete cantilever wall consists of a steel-reinforced concrete wall stem and base slab connected to form the shape of an inverted "T". A CIP concrete counterfort wall is a cantilever wall which employs triangular braces at regular intervals along the length of the wall to provide additional lateral resistance. These walls rely on self-weight plus the weight of soil above the base slab to resist overturning and sliding due to lateral stresses of the retained soil behind the wall. Design procedures are well established for overturning and sliding analyses, and for evaluation of the bearing capacity of the underlying foundation soils. The structural design of a cantilever and counterfort wall assumes that the wall stem and the base slab are fixed at the junction between the two members and act as cantilever beams. Counterforts tie the wall stem and the base slab together and reduce bending moments and shears in the wall members through the transfer of tensile forces in the counterforts. Backfill soil should be free draining to prevent water pressure from acting on the back of the wall.

General

Typical applications:	Bridge abutments, retaining walls, slope stabilization
Unit cost range:	\$270-\$650 per square meter of wall face
Unit cost includes:	Concrete, reinforcing steel, granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Base width ranges from 0.4 to 0.7 of the wall height
Typical height range:	2-9 m (cantilever wall); 9-18 m (counterfort wall)

Advantages

- Conventional wall system with well-established design procedures and performance characteristics.
- Concrete is very durable in many environments.
- Concrete can be formed, textured, and colored to meet aesthetic requirements.
- Counterfort walls undergo less lateral displacement than cantilever walls.



Disadvantages

- Wall system requires a relatively long construction period because formwork must be erected and concrete must be poured and allowed to cure before backfill loads can be applied to the wall.
- Wall system cost will significantly increase if adequate source of select backfill is not available near project site.
- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- Deep foundation support, which increases wall system cost and construction time significantly, may be required if wall is founded on weak or marginal soils.
- Wall system is rigid and is sensitive to total and differential settlement.
- Since counterfort walls typically deflect less than cantilever walls, it may be necessary to design these walls to resist higher earth pressures.
- Wall system is typically not cost-effective for temporary applications.

Primary System Components

- Reinforced concrete
- Granular soil backfill
- Drainage system(s)

Additional Comments

- Batching, placement, and curing times of concrete should be monitored.
- Foundations should be adequately compacted before concrete is placed.
- Wall stems which are less than 3 m in height are typically constructed with constant cross-sectional thickness.
- Resistance to sliding can be increased by constructing a key into the underlying foundation.
- Counterfort walls are used for situations in which unusually high pressures are expected to act on the back of the wall or for wall heights generally greater than 9 m.
- L-shaped cantilever wall may be necessary in areas with strict right-of-way requirements.

Counterfort wall prior to backfilling

ERS SUMMARY NO. 3: Crib Wall

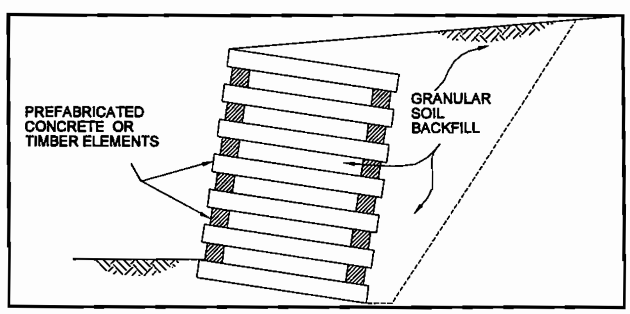
Category of Wall: Prefabricated Modular Gravity Wall
Classification of Wall: Externally Stabilized Fill Wall

Description
A concrete crib wall is a gravity retaining structure constructed of interlocking prefabricated reinforced or unreinforced concrete elements. Timber crib walls can be constructed of either stacked "log-cabin style" prefabricated timber elements or stacked timber beams that are nailed together using steel spikes. Each crib is comprised of alternating transverse and longitudinal horizontal beams. Each crib unit is filled with granular, free draining soil, which is compacted inside each unit. Design of a crib wall for global stability is similar to that of a CIP concrete gravity wall. The weight of a soil-filled crib unit resists overturning and sliding due to the lateral stresses of the retained soil behind the wall. Backfill soil should be free draining to prevent water pressure from acting on the back of the wall.

General

Typical applications:	Retaining walls, slope stabilization
Unit cost range:	$270-$380 per square meter of wall face
Unit cost includes:	Precast concrete or timber elements, granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Base width ranges from 0.5 to 0.7 of the wall height
Typical height range:	2-11 m
Commercially-available systems:	Criblock® (concrete); Permacrib® (timber)

Advantages
- Construction is rapid and does not require specialized labor or equipment.
- Wall elements are relatively small in size.
- Wall system construction does not require heavy equipment.



Disadvantages
- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- On-site design changes are difficult since components are prefabricated off-site.
- Limited space within bins makes use of hand compaction equipment necessary.
- Standard components may require modification for use in wall systems with significant

horizontal curvature.

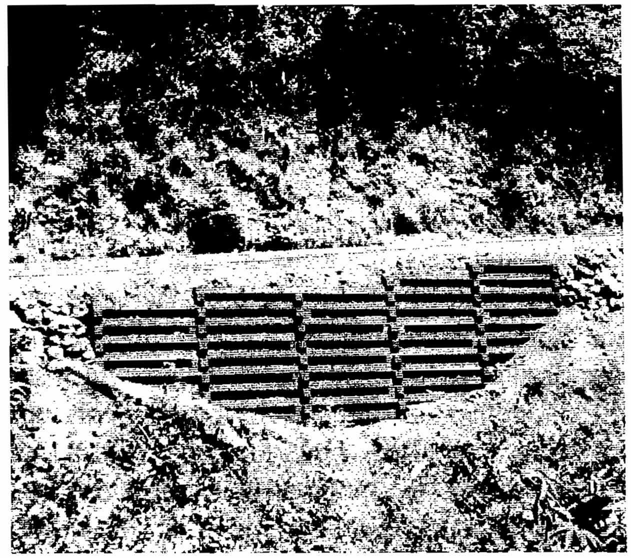
- Wall system can only accommodate minor differential settlements.
- Wall system is typically not cost-effective for temporary applications.

Primary System Components

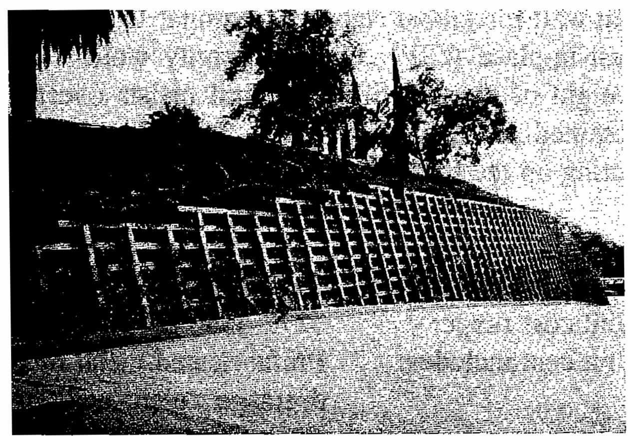
- Prefabricated concrete or timber elements
- Granular soil backfill (inside crib units and behind wall)
- Drainage system(s)

Additional Comments

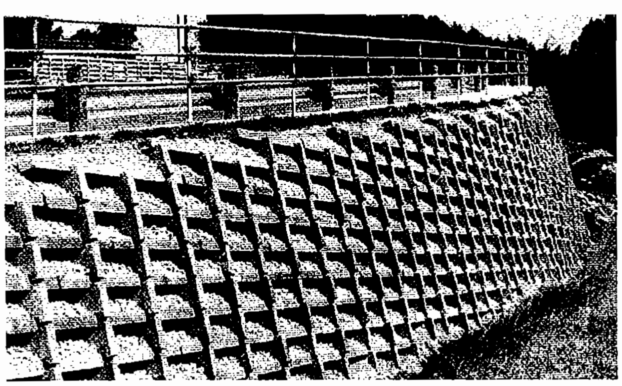
- Proper compaction of fill in the crib units is necessary to minimize wall settlement and distortion.
- At a given level, the fill inside the crib units should be placed and compacted prior to backfilling behind the wall.
- Walls can be constructed with batters.
- Open-faced crib walls require coarsely graded backfill or filter protection such as a geotextile to prevent flow of soil through openings in the face of the wall.



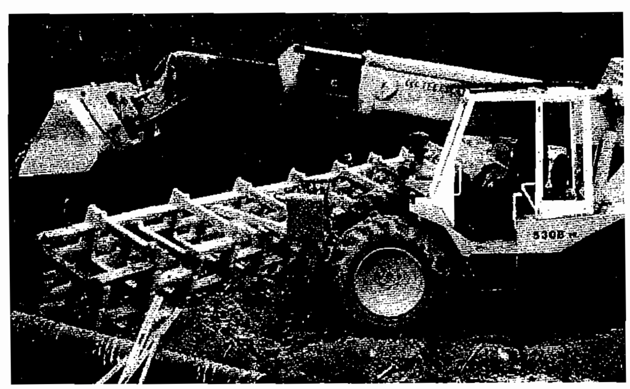
Completed timber crib wall



Completed concrete crib wall



Completed concrete crib wall



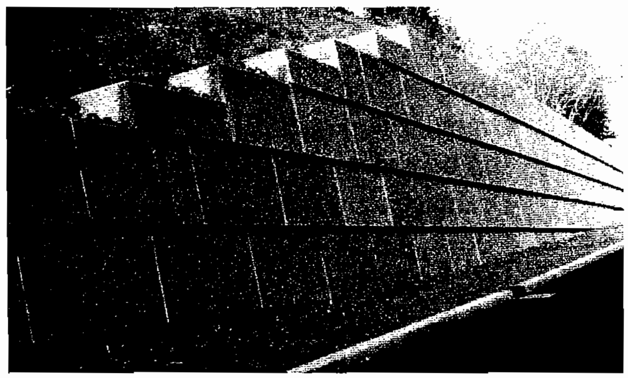
Concrete crib wall being backfilled

ERS SUMMARY NO. 4: Bin Wall

Category of Wall: Prefabricated Modular Gravity Wall
Classification of Wall: Externally Stabilized Fill Wall

Description

Concrete and metal bin walls are gravity retaining structures built of adjoining closed-face or open-face bins. Each unit of a metal bin wall is comprised of lightweight steel members which are bolted together on-site. Each unit of a concrete bin wall is comprised of interlocking prefabricated reinforced concrete modules that are placed like building blocks. Each bin unit is filled with granular, free-draining soil which is compacted inside each unit. Design of a metal or concrete bin wall for global stability is similar to that of a cast-in-place (CIP) concrete gravity wall. The weight of the soil-filled bin unit resists overturning and sliding due to the lateral stresses of the retained soil behind the wall. Backfill soil should be free draining to prevent water pressure from acting on the back of the wall.



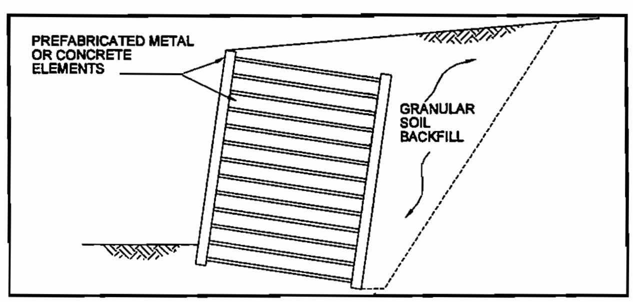
Completed concrete bin wall

General

Typical applications:	Retaining walls, slope stabilization
Unit cost range:	$270-$380 per square meter of wall face
Unit cost includes:	Prefabricated metal or reinforced concrete elements, granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Base width ranges from 0.5 to 0.7 of the wall height
Typical height range:	2-11 m
Commercially-available systems:	Contech®; Syro Steel® (metal) Doublewal®; Evergreen®; Stresswall®; Stawal® (concrete)

Advantages

- Construction is rapid and does not require specialized labor or equipment.
- Wall system does not require significant maintenance.
- Closed-face bins prevent the loss of backfill.



Disadvantages

- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- On-site design changes are difficult since components are pre-fabricated off-site.
- Limited space within bins makes use of hand compaction equipment necessary.
- Standard components may require modification for use in wall systems with significant horizontal curvature.
- Soil erosion can occur in open-faced bin walls.
- Wall system can only accommodate minor differential settlements.
- Metal bin walls are subject to corrosion in aggressive soils.
- Wall system is typically not cost-effective for temporary applications.


Backfilling of concrete bin wall

Primary System Components

- Prefabricated metal or reinforced concrete elements
- Granular soil backfill (inside bin units and behind wall)
- Drainage system(s)

Additional Comments

- Proper compaction of fill in the bin units is necessary to minimize wall settlement and distortion.
- At a given level, the fill inside the bin units should be placed and compacted prior to backfilling behind the wall.
- Walls can be constructed with batters.
- Metallic elements can be galvanized or aluminized for corrosion protection.


Completed metal bin wall

ERS SUMMARY NO. 5: Gabion Wall

Category of Wall: Prefabricated Modular Gravity Wall
Classification of Wall: Externally Stabilized Fill Wall

Description

Gabion walls are compartmented units filled with stone that is 100 to 200 mm in size. Each unit is a rectangular basket made of galvanized steel, geosynthetic grid, or polyvinylchloride (PVC)-coated wire. Each gabion unit is laced together on-site and filled with select stone. Design of a gabion wall for global stability is similar to that of a cast-in-place (CIP) concrete gravity wall. Gabion walls can be designed with wire mesh or geosynthetic reinforcement that extends back into the retained soil from between the gabion unit. These wall systems are termed tailed gabions. Design of tailed gabions is similar to mechanically stabilized earth (MSE) walls.

General

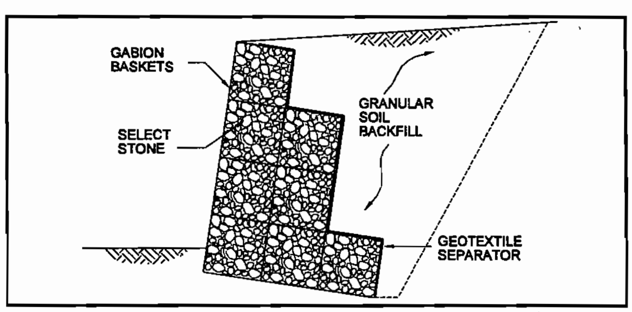
Typical applications:	Retaining walls, slope stabilization, bank stabilization
Unit cost range:	$270-540 per square meter of wall face
Unit cost includes:	Gabion baskets, select stone, granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Base width ranges from 0.5 to 0.7 of the wall height
Typical height range:	2-8 m
Commercially-available systems:	Maccaferri Gabion; Terra Aqua; Hilfiker (gabion) Maccaferri Teramesh System; Tensar Structural Gabions (tailed gabion)

Advantages

- Wall system is flexible and can accommodate large total and differential settlements without distress.
- Wall appearance well-suited to rural areas.
- Since wall system is flexible, it is well-suited for applications in regions of high seismicity.
- Wall system is pervious and is therefore well-suited for bank stabilization applications.

Disadvantages

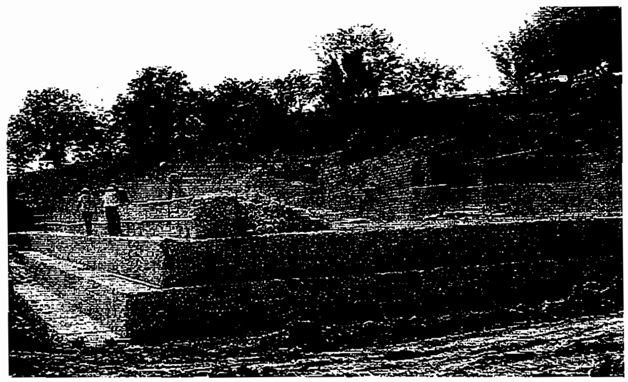
- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- Source of stone must be available nearby for wall system to be economical.



- Gabion wire baskets are subject to corrosion in aggressive soils.
- Construction of wall system requires significant manual labor.
- Abrasion of the gabion baskets may occur in waterway applications where flowing water contains heavy sediment.
- Wall system is typically not cost-effective for temporary applications.

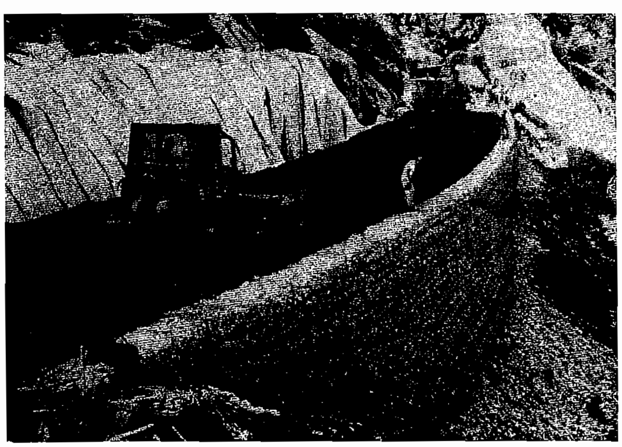
Primary System Components

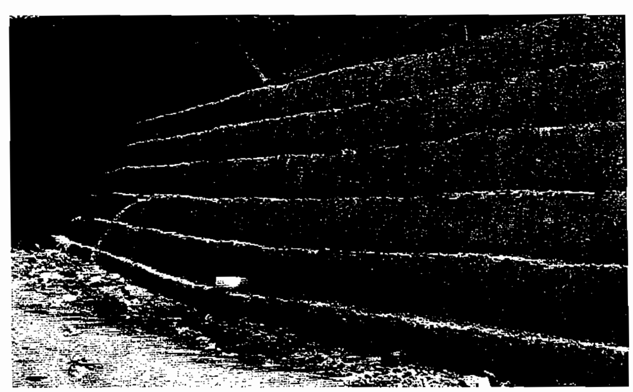
- Gabion baskets
- Select stone
- Granular soil backfill
- Geotextile separator
- Drainage system(s)


Construction of gabion wall

Additional Comments

- Stone must be placed tightly to maximize weight of gabion units and to minimize wall settlement and distortion due to shifting of stone fill.
- Sharp and/or irregular asperities must be removed from foundation to avoid cutting gabion basket wires.
- Outer stone layer along all exposed gabion faces should be hand-placed to ensure proper alignment.
- Wall system is highly permeable.
- Gabion counterforts can be used to increase stability against sliding.
- PVC coated or geosynthetic gabions should be used where aggressive soil or water conditions are present.


Backfill being spread behind gabion wall


Completed gabion wall

ERS SUMMARY NO. 6: Segmental, Precast Facing
Mechanically Stabilized Earth (MSE) Wall

Category of Wall: Mechanically Stabilized Earth (MSE) Wall
Classification of Wall: Internally Stabilized Fill Wall

Description

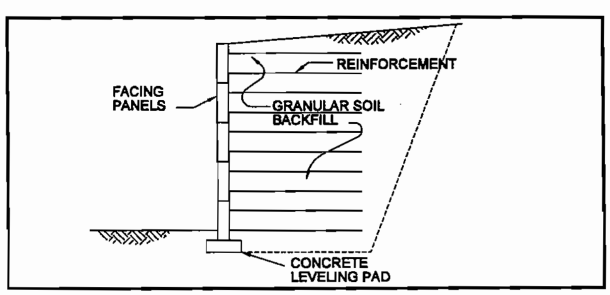
A segmental, precast facing mechanically stabilized earth (MSE) wall employs metallic (strip or bar mat) or geosynthetic (geogrid or geotextile) reinforcement that is connected to a precast concrete or prefabricated metal facing panel to create a reinforced soil mass. The reinforcement is placed in horizontal layers between successive layers of granular soil backfill. Each layer of backfill consists of one or more compacted lifts. A free draining, nonplastic backfill soil is required to ensure adequate performance of the wall system. For walls reinforced with metallic strips, load is transferred from the backfill soil to the strip reinforcement by shear along the interface. For walls with ribbed strips, bar mats, or grid reinforcement, load is similarly transferred but an additional component of strength is obtained through the passive resistance on the transverse members of the reinforcement. Metallic reinforcement and high modulus geosynthetic reinforcement, which are relatively inextensible, require less deformation to mobilize shear strength as compared to geotextiles and lower modulus geogrids. Facing panels are typically square, rectangular, hexagonal, or cruciform in shape and are up to 4.5 m^2 in area.

General

Typical applications:	Bridge abutments, retaining walls, slope stabilization
Special applications:	Seawalls, dams, storage bunkers
Unit cost range:	$240-$380 per square meter of wall face
Unit cost includes:	Facing panels, reinforcement, concrete leveling pad, granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Typical minimum reinforcement length is 0.7 of the wall height
Typical height range:	3-20 m
Commercially-available systems:	Reinforced Earth® (steel strip) Mechanically Stabilized Embankment®; VSL Retained Earth®; Georgia Stabilized Embankment®; Strengthened Earth®; Isogrid® (steel bar mat)

Advantages

- Wall system construction is relatively rapid and does not require specialized labor or equipment.
- Limited foundation preparation is required.
- Wall system is flexible and can

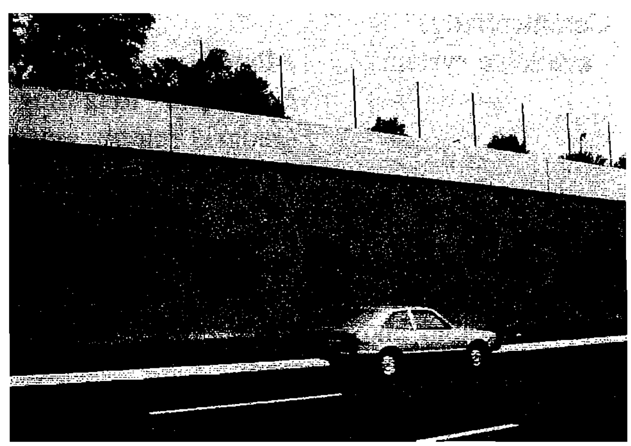


accommodate relatively large total and differential settlements without distress.
- Reinforcement is light and easy to handle.
- Concrete facing panels permit greater flexibility in the choice of facing and architectural finishes.
- Since wall system is flexible, it is well-suited for applications in regions of high seismicity.


Construction of MSE wall

Disadvantages
- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- Wall system requires relatively large base width.
- Use of metallic reinforcement requires that backfill meet minimum electrochemical requirements for corrosion protection.
- Allowable load for geosynthetic reinforcement must be reduced to account for creep, durability, and construction damage.
- Wall system may not be appropriate for applications: (1) where it may be necessary to gain future access to underground utilities; (2) at locations subject to scour; or (3) involving significant horizontal curvature.
- Wall system is typically not cost-effective for temporary applications.

Primary System Components
- Facing panels
- Reinforcement (steel strip, steel bar mat, geosynthetic)
- Concrete leveling pad
- Granular soil backfill
- Drainage system(s)


Completed MSE wall

Additional Comments
- Position and alignment of facing must be monitored to ensure proper fit and appearance.
- Design of metallic reinforcement requires provisions for loss of section thickness due to corrosion over design life.

ERS SUMMARY NO. 7: Prefabricated Modular Block Facing Mechanically Stabilized Earth (MSE) Wall

Category of Wall: Mechanically Stabilized Earth (MSE) Wall
Classification of Wall: Internally stabilized Fill Wall

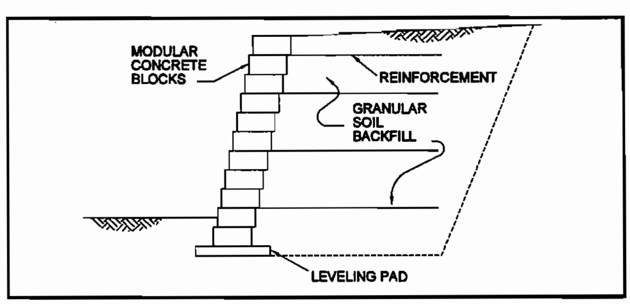
Description
A modular concrete block facing wall consists of vertically stacked, dry cast concrete blocks in which geogrid, metallic grid, or geotextile reinforcement is secured between the blocks at predetermined levels. The reinforcement extends from the blocks into a granular soil backfill. Each layer of backfill consists of one or more compacted lifts. The reinforcement may be connected to the wall face through friction developed between vertically adjacent blocks or through the use of special connectors. The concrete blocks may be solid or have a hollow core. Hollow core blocks are filled with crushed stone or sand during construction. A free draining, nonplastic backfill soil is required to ensure adequate performance of the wall system. Load is transferred from soil to the reinforcement through passive resistance on transverse members of the grid and interface friction between the soil and the surface of the reinforcement.

General

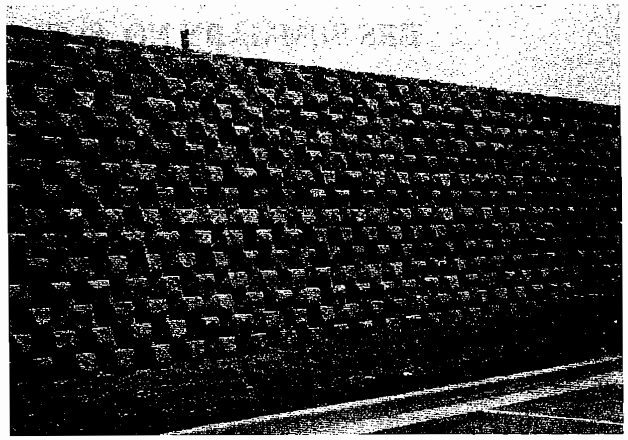
Typical applications:	Retaining walls, slope stabilization
Unit cost range:	\$175-\$275 per square meter of wall
Unit cost includes:	Modular concrete blocks, reinforcement, leveling pad, granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Typical minimum reinforcement length is 0.7 of the wall height
Typical height range:	2-6 m
Commercially-available systems:	Allan Block™ Retaining Walls; Genesis™ Highway Wall System; Newcastle Retaining Wall System; Mesa™ Retaining Wall System (geogrid reinforcement) Pyramid™ (metallic grid reinforcement)

Advantages

- Wall system construction is relatively rapid and does not require specialized labor or equipment.
- Limited foundation preparation is required.
- Wall system is flexible and can accommodate relatively large settlements without distress.
- Modular blocks are relatively light and



easily handled.
- Reinforcement is relatively lightweight and easy to handle.
- Modular blocks permit flexibility in the choice of sizes, shapes, weights, textures, and colors.
- Wall system can adapt to fairly sharp curves and significant front batter.



Completed modular block wall

Disadvantages
- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- Use of metallic reinforcement requires that backfill meet minimum electrochemical requirements for corrosion protection.
- Allowable load for geosynthetic reinforcement must be reduced to account for creep, durability, and construction damage.
- Wall system may not be appropriate for applications where it may be necessary to gain future access to underground utilities or where scour is anticipated.
- Geosynthetic reinforcement may be damaged by oversize backfill or excessive compaction.
- Wall system is typically not cost-effective for temporary applications.

Primary System Components
- Modular concrete blocks
- Reinforcement (geogrid, metallic grid, geotextile)
- Leveling pad (concrete or crushed stone)
- Granular soil backfill
- Drainage system(s)

Construction of modular block wall

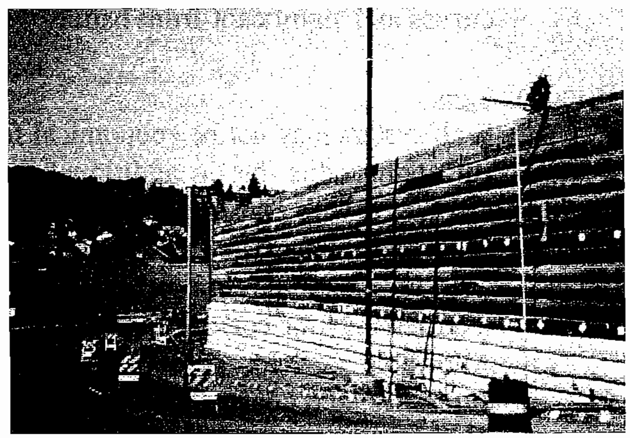
Additional Comments
- Position and alignment of modular concrete blocks must be monitored to ensure proper fit and performance.
- Front batter is usually required to stack modular concrete blocks.
- Freeze-thaw durability of modular blocks can be improved by applying a sealant to the wall face following construction.

ERS SUMMARY NO. 8: Geotextile/Geogrid/Welded Wire Facing Mechanically Stabilized Earth (MSE) Wall

Category of Wall: Mechanically Stabilized Earth (MSE) Wall
Classification of Wall: Internally Stabilized Fill Wall

Description

These wall systems consist of continuous or semi-continuous layers of geotextile, geogrid, or welded wire mesh laid down alternately with horizontal layers of compacted soil backfill. The wall facing is constructed by wrapping each layer of reinforcement around the overlying layer of backfill and then reembedding the free end into the backfill. Each layer of backfill consists of one or more compacted lifts. For permanent wall applications, a free draining, nonplastic soil is required to ensure adequate performance of the wall system. Permanent facings include shotcrete, gunite, galvanized welded-wire mesh, or prefabricated concrete or wood panels.



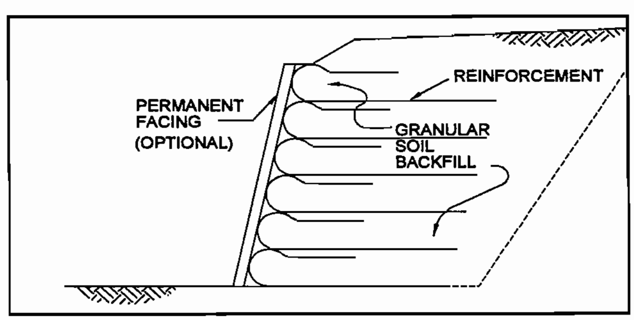
Geotextile wall

General

Typical applications:	Retaining walls, slope stabilization
Special applications:	Sound/noise absorbing embankment wall
Unit cost range:	\$165-\$380 per square meter of wall
Unit cost includes:	Reinforcement, facing elements (if required), granular soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Typical minimum reinforcement length is 0.7 of the wall height
Typical height range:	2-15 m
Commercially-available systems:	Hilfiker Retaining Wall Company (welded wire)

Advantages

- Wall system construction is relatively rapid and does not require specialized labor or equipment.
- Limited foundation preparation is required.
- Wall system is extremely flexible and can accommodate large total and



differential settlements without distress.

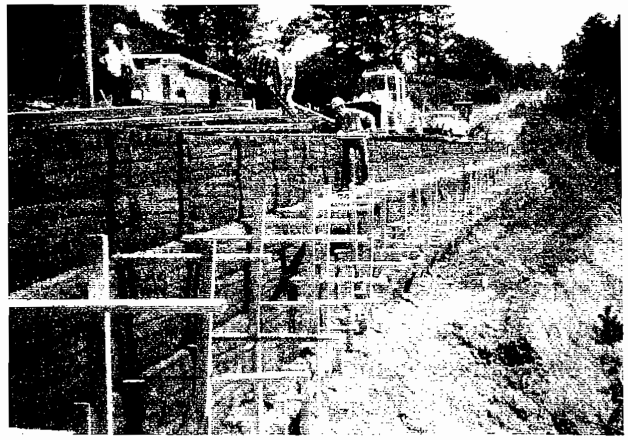
- Reinforcement is light and easy to handle.
- Certain geotextiles may improve drainage characteristics of clayey backfill.
- Since wall system is flexible, it is well-suited for applications in regions of high seismicity.
- Vegetated facing can provide ultraviolet light protection to polymer reinforcement.
- Wall system is often appropriate for temporary applications.

Disadvantages

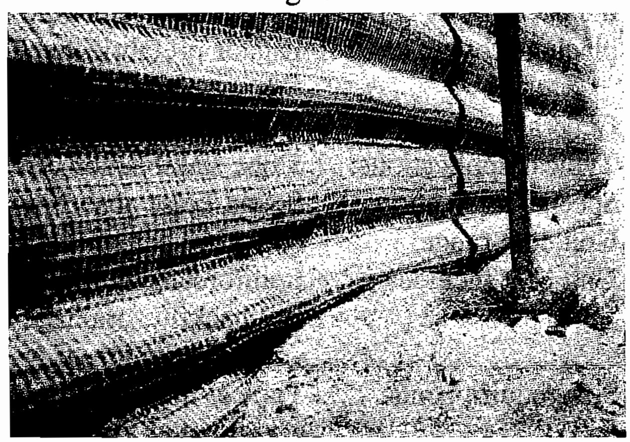
- Wall system may not be economical for cut applications due to additional cost associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- Wall system requires relatively large base width.
- Geotextile or geogrid wall face may not meet aesthetic requirements.
- Geotextile and geogrid life may be reduced due to exposure to ultraviolet light.

Primary System Components

- Reinforcement (geotextile, geogrid, welded wire)
- Facing elements (if required)
- Granular soil backfill
- Drainage system(s)



Geogrid wall



Welded wire wall

Formwork for geotextile wall

Additional Comments

- Appropriate orientation of geotextile sheets or geogrid should be verified on-site.
- Allowable load for geosynthetic reinforcement is reduced by factors accounting for creep, durability, and construction damage.
- Geotextile or geogrid walls require forms to support wall face as lifts are constructed.

ERS SUMMARY NO. 9: Reinforced Soil Slope (RSS)

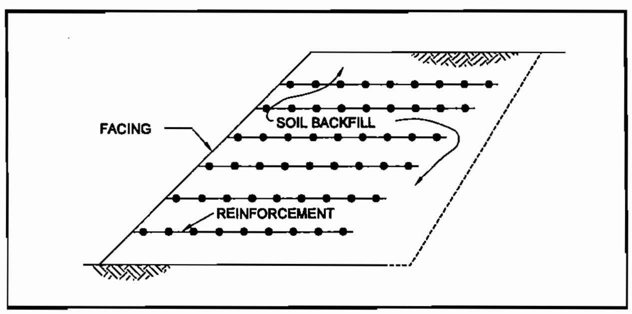
Category of Wall: Reinforced Soil Slope
Classification of Wall: Internally Stabilized Fill Wall

Description
These earth retaining systems incorporate planar reinforcement, typically geotextile or geogrid, in constructed earth slopes with face inclinations of less than 70 degrees. The reinforcement is laid down alternately with horizontal layers of compacted soil backfill. Each layer of backfill consists of one or more compacted lifts. If slope facing is used to prevent erosion or provide a desired appearance, the facing may be constructed by: (1) extending reinforcement layers outside the slope face and wrapping each layer around the overlying backfill and then reembedding the free end into the backfill; or (2) extending reinforcement to slope face and then either vegetating the face, or placing erosion control mats or prefabricated elements against the slope face.

General

Typical applications:	Slope stabilization, embankment construction
Special applications:	Sound/noise absorbing embankment wall
Unit cost range:	$80-$260 per square meter of wall
Unit cost includes:	Reinforcement, facing elements (if required), erosion control measures, soil backfill, drainage elements, labor, equipment, foundation preparation, and construction of wall and drainage system(s)
Size requirements:	Typical minimum reinforcement length is 0.5 to 1.0 of the wall height; actual length typically varies with face inclination
Typical height range:	3-30 m

Advantages



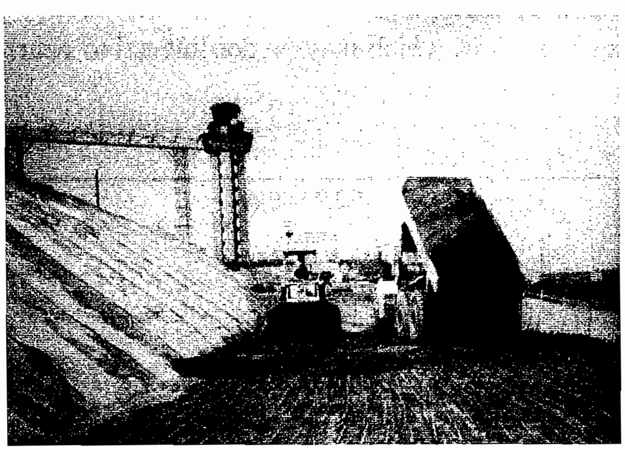
- Wall system construction is relatively rapid and does not require specialized labor or equipment.
- Limited foundation preparation is required.
- Wall system is extremely flexible and can accommodate large total and differential settlements without distress.
- Reinforcement is light and easy to handle.
- Certain geotextiles may improve drainage characteristics of clayey backfill.
- Since wall system is flexible, it is well-suited for applications in regions of high seismicity.
- Lower quality backfill can be used as compared to other fill wall systems.
- Vegetation on slopes can provide ultraviolet light protection to polymer reinforcement

and a pleasing appearance.
- System can be used for the construction of very high embankments and slopes (30 m).

Disadvantages
- Non-vertical slope increases required right-of-way compared to a vertical wall.
- Wall system may not be economical for cut applications due to additional costs associated with constructing temporary excavation support to provide sufficient base width to construct the wall.
- Wall system requires relatively large base width.
- Geotextile or geogrid wall face is irregular and may not meet aesthetic requirements.
- Geotextile and geogrid life may be reduced due to exposure to ultraviolet light.
- Specifications and contracting practices have not been standardized.
- Reinforced soil slopes with vegetated facing may require significant maintenance.

Primary System Components
- Reinforcement (geotextile, geogrid)
- Facing elements (if required)
- Erosion control measures
- Soil backfill
- Drainage system(s)

Additional Comments
- Appropriate orientation of geotextile sheets or geogrid should be verified on-site.
- Allowable load for geosynthetic reinforcement is reduced by factors accounting for creep, durability, and construction damage.
- Geotextile or geogrid walls require temporary forms to support wall face as lifts are constructed.
- Selection of slope vegetation should be based on project site climactic conditions.



Reinforced soil slope during construction

Reinforced soil slope with vegetated face

ERS SUMMARY NO. 10: Sheet-pile Wall

Category of Wall: Non-gravity Cantilevered Wall
Classification of Wall: Externally Stabilized Cut Wall

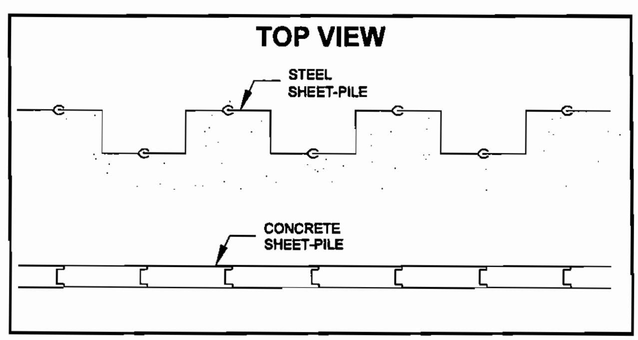
Description
A sheet-pile wall consists of driven, vibrated, or pushed, interlocking steel or concrete sheet-pile sections. The required depth of embedment (i.e., length of sheet-pile below final excavated grade) is evaluated based on the assumption that the passive resistance of the soil in front of the wall plus the flexural strength of the sheet-pile can resist the lateral forces from the soil behind the wall. Sheet-pile walls can be constructed with anchors (see ERS Summary No. 15).

General

Typical applications:	Retaining walls, slope stabilization, excavation support
Special applications:	Marine walls, docks
Unit cost range:	\$160-\$430 per square meter of wall face
Unit cost includes:	Steel or concrete sheet-piles, labor, equipment, and construction of wall
Size requirements:	N/A
Typical height range:	2-5 m

Advantages
- Conventional wall system with well-established design procedures and performance characteristics.
- Wall system can be used for applications in which the wall penetrates below the ground-water table.
- Work area inside wall face is not required.
- Wall system is suitable for temporary applications.

Disadvantages
- Construction of wall system requires specialized equipment.
- Driving sheet-pile is noisy and it can induce vibrations which may be detrimental to nearby structures.
- Sheet-pile interlocks may be lost during driving which will allow water (for walls constructed in areas of high ground water) to advance into the excavation.
- Difficult to drive sheeting in hard or dense soils; also difficult to drive in gravelly soils.
- Wall height is limited based on required structural section.



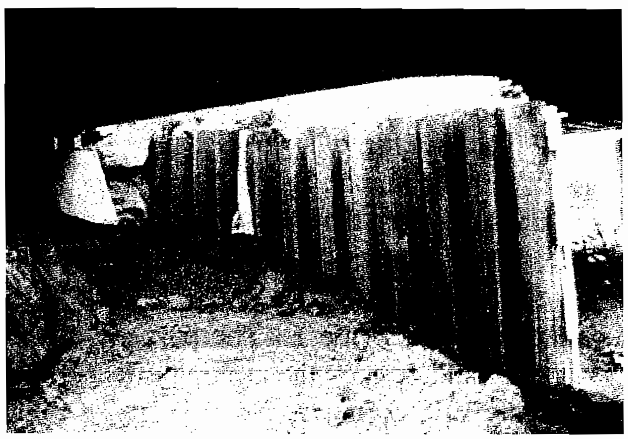
- Wall system may undergo relatively large lateral movements which may be detrimental to nearby structures.

Primary System Components

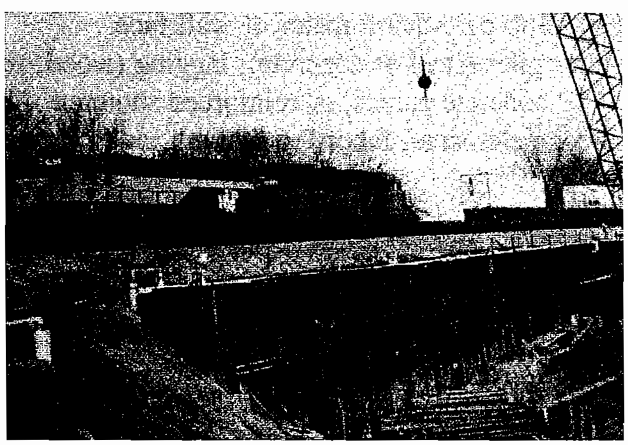
- Steel or concrete sheet-pile

Additional Comments

- Proper selection of pile hammer and cushioning is necessary to avoid tearing of pile interlock and excessive damage at the top of the sheet-pile.
- Wall system is typically used in potentially squeezing or running soils such as soft clays and cohesionless silt or loose sand below the water table.



Temporary sheet-pile wall



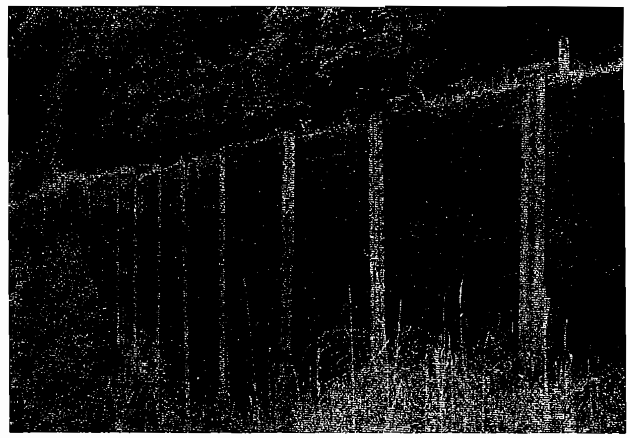
Completed sheet-pile wall

ERS SUMMARY NO. 11: Soldier Pile and Lagging Wall

Category of Wall: Non-gravity Cantilevered Wall
Classification of Wall: Externally Stabilized Cut Wall

Description

A soldier pile and lagging wall is a non-gravity cantilevered wall which derives lateral resistance and moment capacity through embedment of vertical wall elements (soldier piles). The soil behind the wall is retained by lagging. The vertical elements may be drilled or driven steel or concrete piles. These vertical elements are spanned by lagging which may be wood, reinforced concrete, precast or CIP concrete panels, or reinforced shotcrete. The spacing of the lagging varies from 2 to 3 m with a common spacing of 2.4 m. A portion of the load from the retained soil is transferred to the vertical elements through arching; (i.e., load is redistributed away from the lagging to the much stiffer soldier piles). The purpose of the lagging is to prevent the retained soil from eroding, which would destroy the arching effect. Soldier pile and lagging walls can be constructed with anchors (see ERS Summary No. 15).



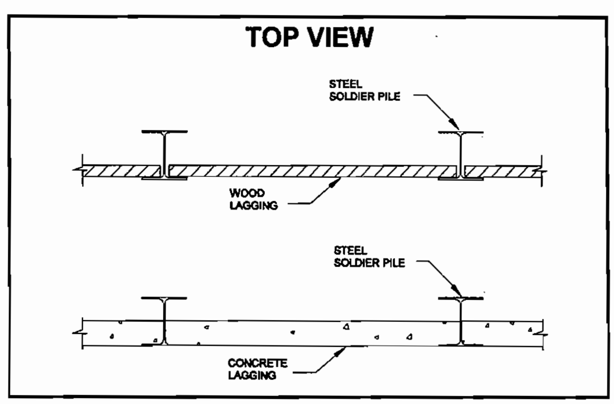
Completed soldier pile and lagging wall

General

Typical applications:	Slope stabilization, temporary excavation support, retaining walls
Unit cost range:	\$110-\$380 per square meter of wall face
Unit cost includes:	Soldier piles (steel or concrete), lagging (wood, reinforced concrete, precast or CIP concrete panels, or reinforced shotcrete), facing panels (if required), drainage elements, labor, equipment, and construction of wall
Size requirements:	N/A
Typical height range:	2-5 m

Advantages

- Conventional wall system with well-established design procedures and performance characteristics.
- Less soldier piles are driven than for the construction of a sheet-pile wall.
- Soldier piles can be drilled or driven.
- Wall system requires minimal work area inside wall face.



- Wall system is suitable for temporary applications.

Disadvantages

- Construction of wall system requires skilled labor and specialized equipment.
- Driving piles is noisy and it can induce vibrations that may be detrimental to nearby structures.
- Difficult to drive piles in hard or dense soils; also difficult to drive in soils with large cobbles and boulders.
- Pre-drilling of soldier piles, if required, is a significant cost component.
- Vibration may induce settlement in loose ground.
- Wall height is limited based on required structural section.
- Wall system may undergo relatively large lateral movements which may be detrimental to nearby structures.

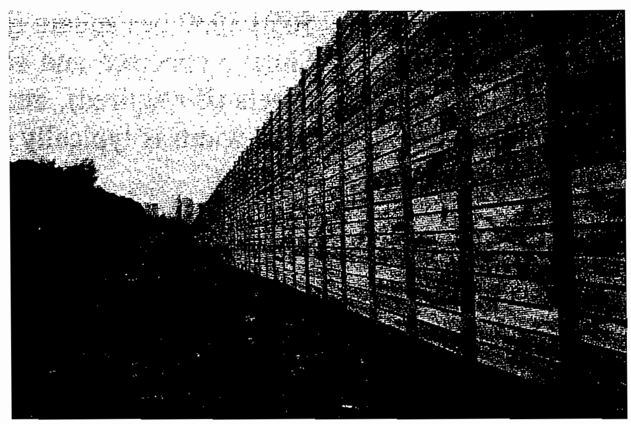
Drilling of soldier beam

Primary System Components

- Soldier piles (vertical wall elements)
- Lagging
- Facing panels (if required)
- Drainage system(s)

Additional Comments

- Construction of wall system in hard clays, shales, or cemented materials enables temporary lagging to be widely spaced or omitted provided soldier piles are sufficiently close.
- Wall system is highly pervious.
- Wall stiffness can be controlled by increasing or decreasing number of soldier piles.
- Wall system develops passive resistance only at the soldier pile locations.



Completed soldier pile and lagging wall

ERS SUMMARY NO. 12: Slurry (Diaphragm) Wall

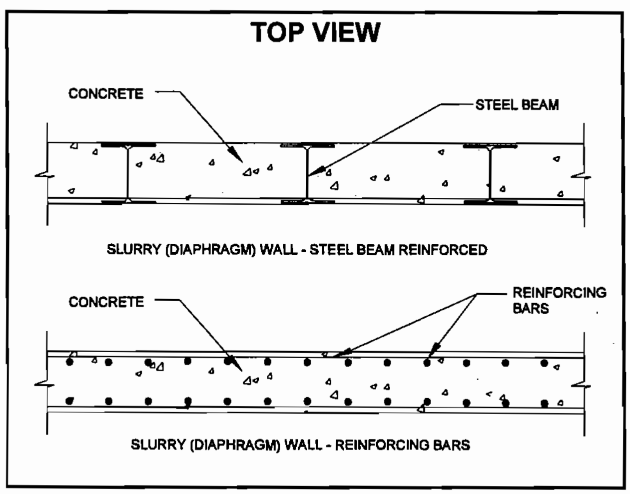
Category of Wall: Non-gravity Cantilevered Wall
Classification of Wall: Externally Stabilized Cut Wall

Description
A slurry (diaphragm) wall is a continuous concrete wall consisting of either steel-reinforced CIP concrete or precast concrete panels that are constructed within an excavated trench. A temporary concrete guidewall is built to maintain the alignment. The trench is constructed from the surface and is stabilized with a mineral or polymer slurry as the excavation proceeds. As an individual section of wall (panel) is excavated, the slurry is cleared of sediments so that subsequently placed tremie concrete will fully displace the slurry. For a CIP panel, a reinforcing cage is inserted into the trench and a high slump concrete is then tremied into the trench. Following a specified set time, the next panel is constructed. After construction, the ground in front of the wall is excavated to final grade. Slurry walls develop earth pressure and moment resistance through embedment. Slurry walls are typically constructed using anchors (see ERS Summary No. 15). Precast or CIP concrete panels may be constructed for permanent applications.

General

Typical applications:	Retaining walls, slope stabilization, excavation support
Special applications:	Cut and cover tunnels, building foundations
Unit cost range:	\$650-\$930 per square meter of wall face
Unit cost includes:	Slurry, concrete and reinforcing steel or precast concrete panels, facing panels (if required), anchors, labor, equipment, and construction of wall
Size requirements:	Wall width is typically 0.4 to 1.0 m
Typical height range:	6-24 m

Advantages
- Wall system is relatively impermeable.
- Lateral movements are relatively small compared to more flexible wall systems.
- Wall system is suitable for construction in all soil types.
- Unobstructed working space can be achieved on-site.
- Wall system construction does not produce significant noise or vibrations.
- Wall system may be used for permanent support of vertical loads.



Disadvantages

- Construction of this system requires specialty contractor and equipment.
- Difficult to obtain a smooth finished wall face.
- Disposal of slurry may be costly due to environmental restrictions.

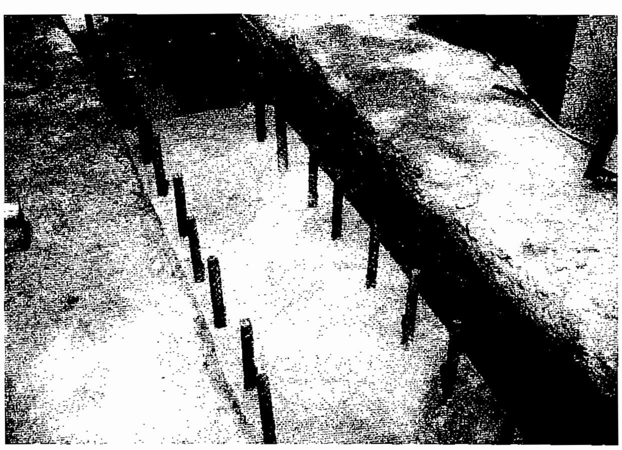
Primary System Components

- Slurry
- Precast or CIP reinforced concrete panels
- Facing panels (if required)
- Anchors

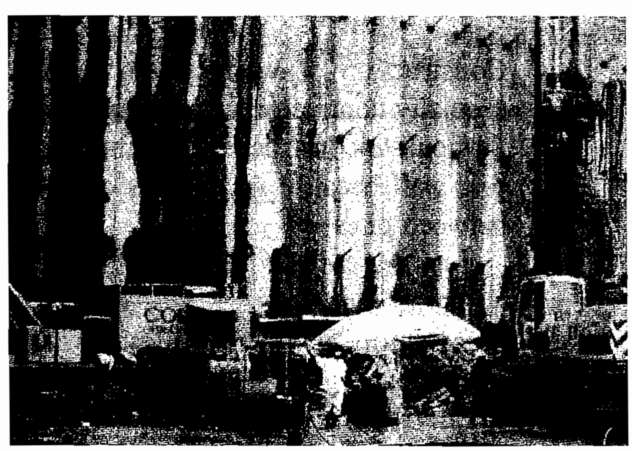
Additional Comments

- Slurry should be tested periodically to ensure that the required specific gravity and viscosity are maintained.
- Concrete placement records should be kept to determine concrete overpours and underpours that would indicate trench collapse.
- Panel connections should be inspected to ensure continuity.
- Panel width is determined by size of excavation tool.

Excavation of trench



Top of wall panel



Completed slurry (diaphragm) wall

ERS SUMMARY NO. 13: Tangent Pile/Secant Pile Wall

Category of Wall: Non-gravity Cantilevered Wall
Classification of Wall: Externally Stabilized Cut Wall

Description

A tangent pile wall consists of a single row of tangentially touching drilled, reinforced-concrete piles. The reinforcement of each pile may consist of a steel beam, a single reinforcing bar, or a reinforcing bar cage. A secant pile wall consists of a single line of alternating drilled, reinforced and unreinforced concrete piles. Alternating unreinforced piles are constructed and allowed to set for a short period of specified time. Subsequently, a reinforced concrete pile is constructed between the previously drilled piles by cutting through a section of the previously constructed concrete piles. Tangent pile and secant pile walls can be constructed with anchors (see ERS Summary No. 15). Precast or CIP concrete panels may be constructed for permanent applications.

General

Typical applications:	Retaining walls, excavation support
Unit cost:	\$430-\$810 per square meter of wall face
Unit cost includes:	Concrete, reinforcing steel, facing panels (prefabricated or CIP), anchors (if required), labor, equipment, and construction of wall
Size requirements:	Pile diameter is typically 0.5 to 1.0 m
Typical height range:	3-9 m without anchors; 6-24 m with anchors

Advantages

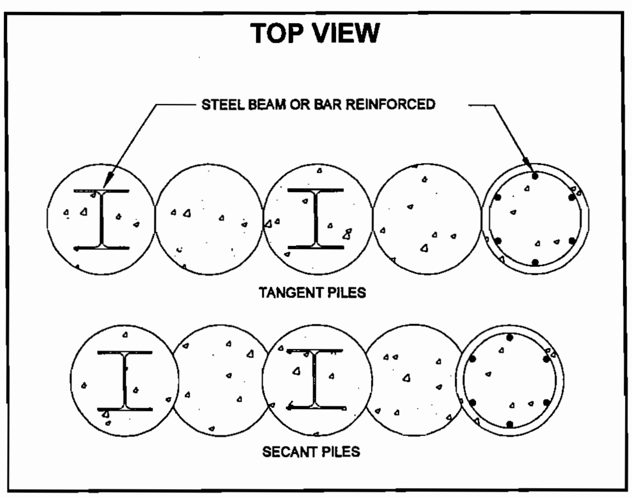
- Lateral movements of these wall systems are relatively small compared to more flexible wall systems.
- Wall system is adaptable to an irregular installation arrangement and is also well-suited for wall alignments with significant horizontal curves.

Disadvantages

- Construction of wall system requires specialty contractor and equipment.
- Difficult to construct watertight tangent pile wall because small gaps can exist between piles.

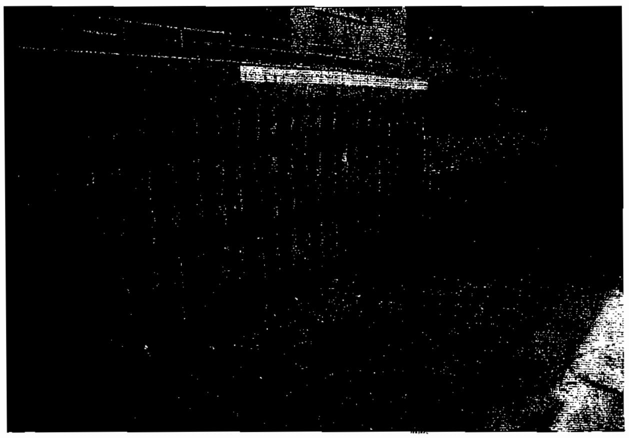
Primary System Components

- CIP reinforced concrete piles
- Facing panels (if required)
- Anchors (if required)



Additional Comments

- Vertical alignment must be maintained to eliminate gaps between tangent piles.
- Wall systems are typically permanent.
- Watertight tangent pile wall can be constructed by installing a second row of smaller piles behind first row of piles.



Tangent pile wall

Drilling of anchors for tangent pile wall

ERS SUMMARY NO 14: Soil Mixed Wall (SMW)

Category of Wall: Non-gravity Cantilevered Wall
Classification of Wall: Externally Stabilized Cut Wall

Description

A soil mixed wall consists of overlapped soil-cement columns in which in-situ soils are mixed with a cement slurry or other hardening agent. A multiple axis auger and mixing paddles are used to construct overlapping soil-cement columns without soil removal or unmixed zones between columns. Steel structural members are typically used for reinforcement and are placed into alternating columns before substantial hardening of the soil-cement takes place. The unreinforced soil-cement columns are designed to resist and redistribute horizontal stress to adjacent reinforced members. Soil mix walls are typically constructed using anchors (see ERS Summary No. 15). Precast panels or CIP concrete may be constructed for permanent applications.

General

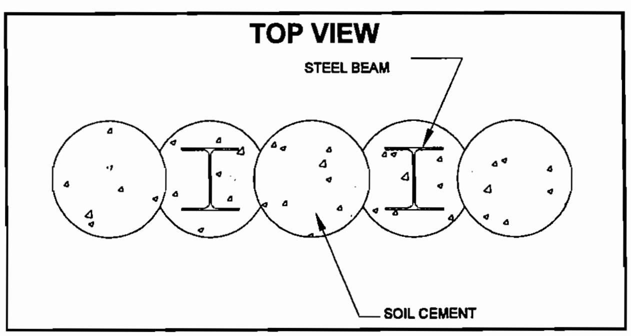
Typical applications:	Retaining walls, excavation support
Unit cost range:	$430-$590 per square meter of wall face
Unit cost includes:	Cement slurry or other hardening agent, reinforcing steel, facing panels (if required), anchors, labor, equipment, and construction of wall
Size requirements:	Soil-cement column diameter is typically 1.0 m
Typical height range:	6-24 m with anchors

Advantages

- Reduced excavated spoil is produced as compared to slurry (diaphragm) walls.
- Wall system is adaptable to an irregular installation arrangement.

Disadvantages

- Design procedures are not well-established.
- Construction of wall system requires specialty contractor and equipment.
- When exposed to freeze-thaw cycles, soil-cement surface may form layers that flake away from the surface.
- Quality control/quality assurance protocol is not well-documented for this wall system.
- Disposal of excavated spoil resulting from the soil mixing process may be costly due to environmental restrictions.
- Special anchor details are required to maintain water-tightness.

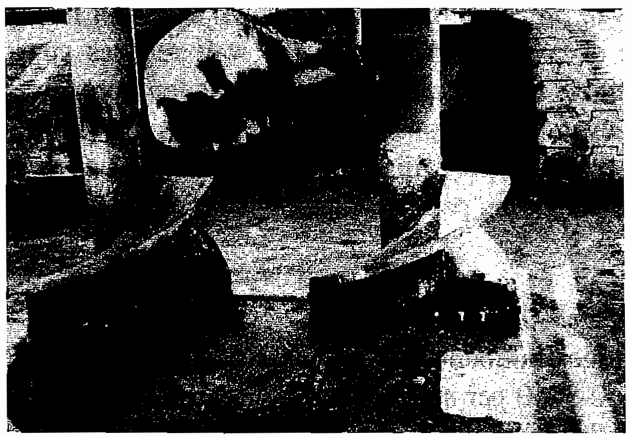


Primary System Components

- Cement slurry or other hardening agent
- CIP unreinforced and reinforced soil-cement columns
- Facing panels (if required)
- Anchors

Additional Comments

- Samples of soil-cement should be obtained for laboratory strength testing.
- Continuity of soil-cement requires careful quality assurance and quality control during construction.
- Wall system can be designed to be relatively impermeable.
- Required engineering properties can be achieved through proper mix design of soil-cement.



Mixing augers

Completed soil mixed wall

ERS SUMMARY NO. 15: Anchored Wall

Category of Wall: Non-gravity Cantilevered Wall
Classification of Wall: Externally Stabilized Cut Wall

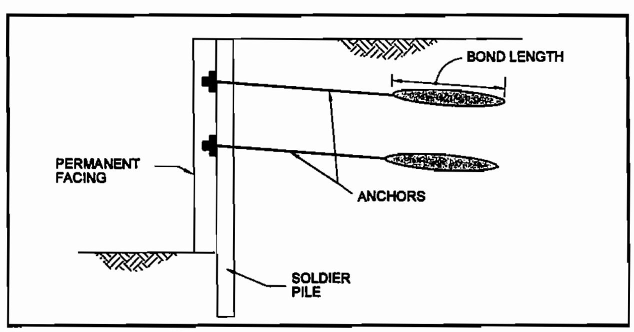
Description
An anchored wall is any non-gravity cantilevered wall (i.e., sheet-pile wall, soldier pile and lagging wall, slurry (diaphragm) wall, tangent pile/secant pile wall, or soil mixed wall (SMW)) which relies on one or more levels of ground anchors (tiebacks) or deadman anchors for additional lateral support. The use of anchors enables these walls to be higher and deflect less than walls without anchors, (i.e., cantilever walls). An anchor is a structural system designed to transmit tensile loads to the retained soil behind a potential slip surface. Construction of the vertical wall elements and lagging (if required) for an anchored wall proceeds from the top-down as for all non-gravity cantilevered walls. When the elevation of the excavation in front of the wall reaches approximately 1 m below the specified elevation of an anchor, the process of excavation is temporarily suspended and anchors are installed at the specified elevation. An anchor is installed using drilling and grouting procedures consistent with the anchor type and prevailing soil conditions. Each anchor is tested following its installation. Typical permanent facing panels include CIP or precast concrete with natural, textured, or architectural finishes.

General

Typical applications:	Bridge abutments, retaining walls, slope stabilization, excavation support
Unit cost range:	\$160-\$810 per square meter of wall face
Unit cost includes:	Soldier piles (steel or concrete), lagging (wood, reinforced concrete, precast or CIP concrete panels, or reinforced shotcrete), facing panels (if required), drainage elements, anchors, grout, labor, equipment, construction of wall, and installation, proof testing, and stressing of anchors
Size requirements:	Unbonded anchor length is typically 0.6 of wall height; actual length depends on minimum specified total anchor length and distance to a bearing strata
Typical height range:	5-20 m

Advantages

- Design procedures for anchors are well-established.
- Unlike internally braced excavations, an unobstructed working space can be achieved on the excavation side of the wall for an anchored wall.
- Relatively large horizontal earth pressures can be resisted by an anchored wall.
- Quality assurance is achieved through

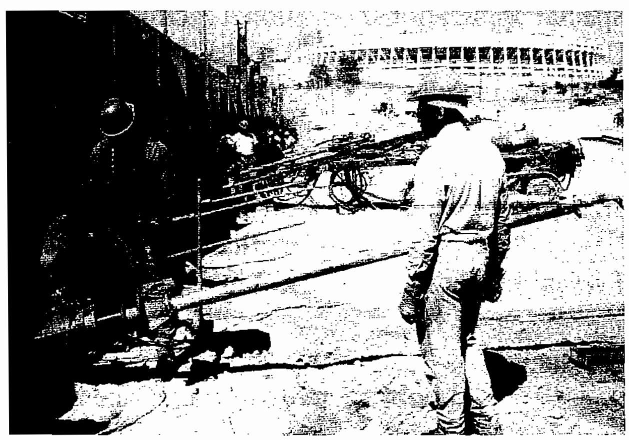


proof testing of each anchor.
- Wall system is suitable for temporary applications.

Disadvantages
- Construction of wall system requires skilled labor and specialized equipment.
- Underground easement may be required for anchors and anchor zone.
- Anchors may be difficult to construct where underground structures or utilities exist.
- Anchor capacity may be difficult to develop in some cohesive soils.


Anchor testing

Primary System Components
- Soldier piles
- Lagging
- Facing panels (if required)
- Drainage system(s)
- Anchors


Grouting and removing casing

Additional Comments
- Corrosion protection of anchors is based on aggressiveness of soil and proposed design life (i.e., temporary or permanent) of wall system.
- Lateral movements associated with excavation can be minimized through prestressing of the anchors.
- Boring must be made behind wall face to identify materials in anchor bond zone.


Completed anchored wall

ERS SUMMARY NO. 16: Soil-Nailed Wall

Category of Wall: In-situ Reinforced Wall
Classification of Wall: Internally Stabilized Cut Wall

Description

Soil nailing is an in-situ soil reinforcement technique wherein passive inclusions (soil nails) are placed into the natural ground at relatively close spacing (e.g., 1.0 to 2.0 m) to increase the strength of the soil mass. Construction is staged from the top-down and, after each stage of excavation, the nails are installed, drainage systems are constructed, and shotcrete is applied to the excavation face. If the wall is permanent, shotcrete or precast or CIP concrete facing panels may be installed after the wall is complete.

General

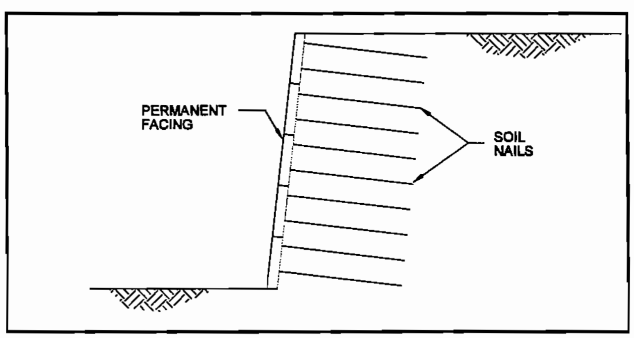
Typical applications:	Retaining walls, slope stabilization, excavation support, widening under existing bridge
Special applications:	Tunnel facing support
Unit cost range:	$160-$600 per square meter of wall face
Unit cost includes:	Shotcrete, facing panels (if required), drainage elements, soil nails, grout, labor, equipment, construction of wall and drainage system(s), and installation and field testing of nails
Size requirements:	Soil nail length typically ranges from 0.6 to 1.0 of the wall height; actual length depends on nail spacing and competency of in-situ soils
Typical height range:	3-20 m

Advantages

- An unobstructed working space can be achieved on the excavation side of the wall.
- Surface movements can be limited by installing additional nails or by stressing nails in upper level to small percentage of working loads.
- Wall system is adaptable to varying site conditions.
- Wall system is well-suited for construction in areas of limited headroom.
- Wall embedment is not required as with other cut wall systems.
- Wall system is suitable for temporary applications.

Disadvantages

- Construction of wall system requires experienced contractor.
- Underground easements for nails may be necessary.
- Construction of wall system below ground water requires that slope face be permanently dewatered.

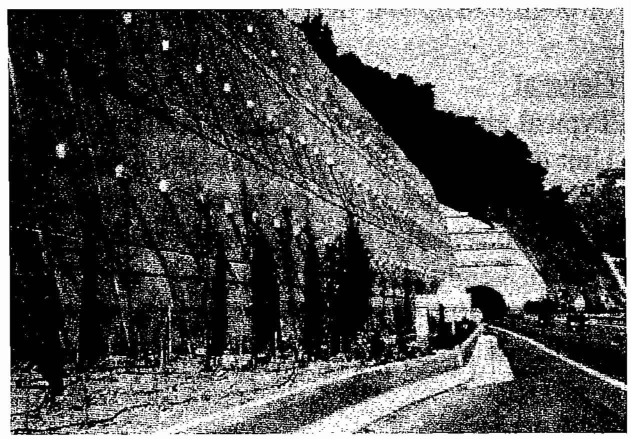


- Closely spaced nails may interfere with underground utilities.
- Nail capacity may be difficult to develop in some cohesive soils.

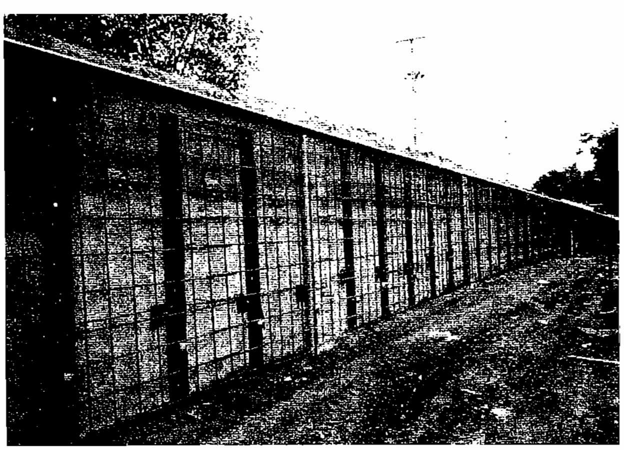
Primary System Components
- Shotcrete
- Permanent facing (if required)
- Drainage system(s)
- Soil nails

Additional Comments
- Initial depths of excavation should be decreased if wall face cannot be supported prior to shotcreting.
- Continuity in vertical drains from level to level must be ensured.
- Wall system performance relies on rapid placement of nails and shotcrete after each stage of excavation.
- Nails must be designed with appropriate corrosion protection schemes.

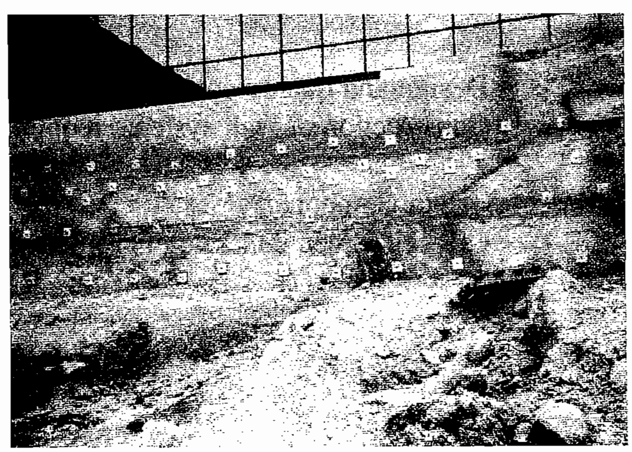
Installation and grouting of soil nails



Soil-nailed wall with precast concrete facing panels



Soil-nailed wall before construction of permanent facing



Completed temporary soil-nailed wall

ERS SUMMARY NO. 17: Micropile Wall

Category of Wall: In-situ Reinforced Wall
Classification of Wall: Internally Stabilized Cut Wall

Description

Micropile walls (i.e., root-pile walls and insert walls) consist of an array of drilled and grouted micropiles that penetrate below a potential surface of sliding. For these wall systems, the micropiles are connected at the ground surface to a reinforced concrete cap beam. The design of a root-pile wall uses small diameter piles spaced closely together in a complex three-dimensional network. The purpose of this micropile system is to "knit" the soil into a coherent mass that behaves as a gravity-retaining structure. The vertical and battered piles of an insert wall are larger in diameter and are spaced farther apart in comparison to a root-pile wall. This wall system provides sliding resistance through tensile and flexural resistance developed in the piles.

General

Typical applications:	Slope stabilization, ground reinforcement, landslide stabilization and repair
Unit cost:	\$3200-\$9800 per linear meter of wall
Unit cost includes:	Concrete, reinforcing steel, grout, labor, equipment, and construction of wall
Size requirements:	Cap beam width is typically 2.0 m
Typical height range:	N/A
Commercially-available systems:	Nicholson Construction - Insert Wall^{SM} (type A)

Advantages

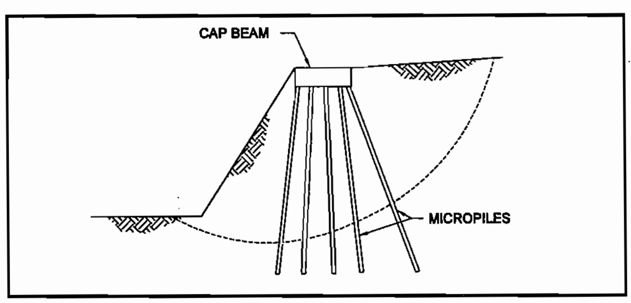
- Methods are well-suited to landslide stabilization since they do not require excavation that could induce movements in unstable or marginally stable slopes.
- Aesthetics is not an issue since wall is buried.

Disadvantages

- Design and quality control/quality assurance procedures are not well established.
- Construction of wall systems require a specialty contractor.

Primary System Components

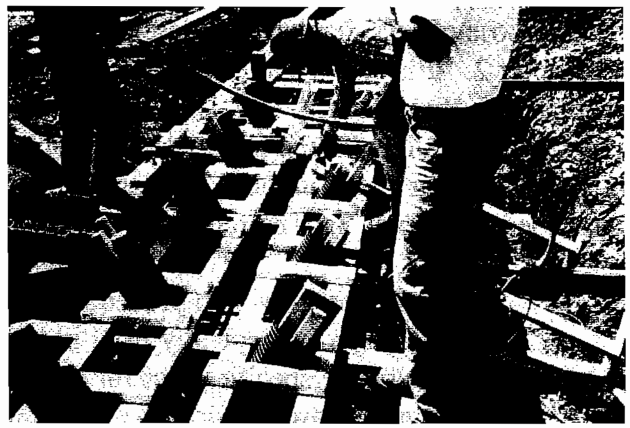
- CIP reinforced concrete micropiles



Additional Comments

- Wall system behavior is influenced by complex soil-pile interaction.
- Cost of wall system is influenced by depth of assumed slip surface.

Excavation for cap beam



Formwork for cap beam

Concrete pour for cap beam

Installation of micropiles

CHAPTER 3

CONSTRUCTION OF EARTH RETAINING SYSTEMS

3.1 INTRODUCTION

The purpose of this chapter is to describe the construction of the earth retaining systems introduced in chapter 2. It is convenient to describe the construction of these systems according to their general method of construction, that is, fill or cut wall construction. The sequence of construction, construction equipment and materials, and constructability issues are described for each of the fill and cut wall systems listed in table 2. Common construction problems and construction inspection are described in chapter 7. The remainder of this chapter is organized as described below.

- A general, step-by-step procedure for the construction of fill walls is presented in section 3.2. Equipment typically used in the construction of fill wall systems is also described. Relevant code specifications for the construction materials and procedures used with these wall systems are provided.

- Similar information to that described above is provided for cut wall systems in section 3.3.

Table 2. Fill and cut wall systems.

Fill Walls	Cut Walls
Rigid Gravity and Semi-Gravity Walls Prefabricated Modular Gravity Walls Mechanically Stabilized Earth (MSE) Walls Reinforced Soil Slopes (RSS)	Non-Gravity Cantilevered Walls • Soldier Pile and Lagging Walls • Sheet-Pile, Tangent Pile, and Secant Pile Walls • Slurry (Diaphragm) Walls • Soil Mixed Walls (SMW) Anchored Walls Soil-Nailed Walls Micropile Walls

3.2. FILL WALL CONSTRUCTION

3.2.1 General

Fill walls represent the most common category of earth retaining system. These wall systems are generally associated with embankment construction where right-of-way (ROW) is not available for the construction of stable slopes to original grade, situations in which obstructions interfere with the placement of fill slopes, or bridge abutment construction.

Common characteristics relating to the construction of all fill wall systems include the preparation of the wall foundation, the placement and compaction of select fill behind the wall, and the installation of drainage systems. Key characteristics of the different types of fill walls are given below. An overview of the construction materials and procedures used with fill wall systems is presented in the following subsections of this document.

- *Rigid Gravity and Semi-Gravity Walls*: These wall systems utilize gravity, cantilevered, or counterforted concrete construction. The placement of select fill occurs after the wall has been constructed.

- *Prefabricated Modular Gravity Walls*: These wall systems utilize off-site prefabricated concrete, steel, timber, or basket enclosures that are filled with either granular fill or rock. These enclosures are assembled, erected, and filled on-site. The placement of select fill occurs as the wall is being constructed.

- *Mechanically Stabilized Earth (MSE) Walls*: These wall systems utilize off-site prefabricated facing units and metallic or geosynthetic soil reinforcing elements that are erected on-site. The placement of select fill occurs as the wall facing is being constructed.

- *Reinforced Soil Slopes (RSS)*: These systems utilize soil reinforcing elements (typically geosynthetics) for the construction of stable earth slopes. The placement of fill occurs just after each layer of reinforcement is placed.

Drainage systems are required for all fill wall systems. A major cause of unsatisfactory performance of fill wall systems has been improperly designed or poorly constructed drainage systems. Drainage systems typically include slotted drain pipes which run parallel to the wall alignment and which are generally located at the rear of the reinforced soil mass for MSE walls and RSS, and just behind the heel of the wall base or the back of the wall for other fill wall systems. Drain outlets are connected to the drain pipes at regularly spaced intervals and serve to transport water collected in the drain pipes away from the wall.

3.2.2 Rigid Gravity and Semi-Gravity Walls

The sequence of construction for rigid gravity and semi-gravity walls is described below.

- The first stage of construction consists of excavating to the wall foundation grade and preparing the wall foundation. If stable excavation slopes cannot be maintained during the period of wall construction, temporary excavation support needs to be provided. Foundation preparation includes removing unsuitable materials such as organic matter and vegetation from the area to be occupied by the wall and leveling and proofrolling the foundation area. Preparation of the wall foundation is extremely important as it must be relatively stiff and uniform, since rigid concrete walls cannot tolerate significant differential settlement. For walls founded on compressible soils, foundation preparation may require ground improvement to increase bearing capacity and stiffness or the construction of deep foundations (i.e., piles or drilled shafts) for wall footing support.

- The footing outline is formed and the reinforcing steel, if any, for the footing is placed. If a cantilever or counterfort wall is to be constructed, the reinforcing steel is extended into the wall stem. For a counterfort wall, reinforcing steel is also extended into the counterforts. The footing concrete is then poured.

- The wall stem is formed and concrete is poured. For counterfort walls, reinforcing steel for the counterforts is placed and the counterforts are then formed and the concrete is poured. Typically, concrete is poured in sections between expansion joints and, wherever possible, it is poured for the full wall height to eliminate cold joints.

- Drainage systems are then constructed behind the wall. Concurrent with this activity is the placement and compaction of select fill to finished grade. Care should be taken to ensure that the backfill soils are not overcompacted just behind the wall face. Overcompaction can induce large lateral earth pressures which may overstress the wall and, if prefabricated drainage material is constructed against the back wall face, damage the drainage component.

Figures 4 through 6 illustrate several stages of construction for these wall systems.

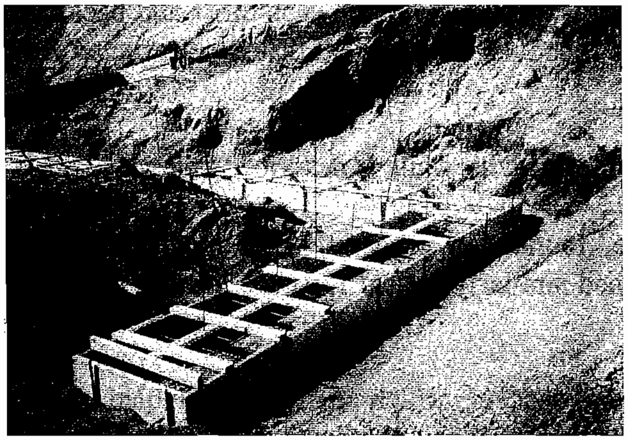


Figure 4. Form outline for cantilever wall footing.

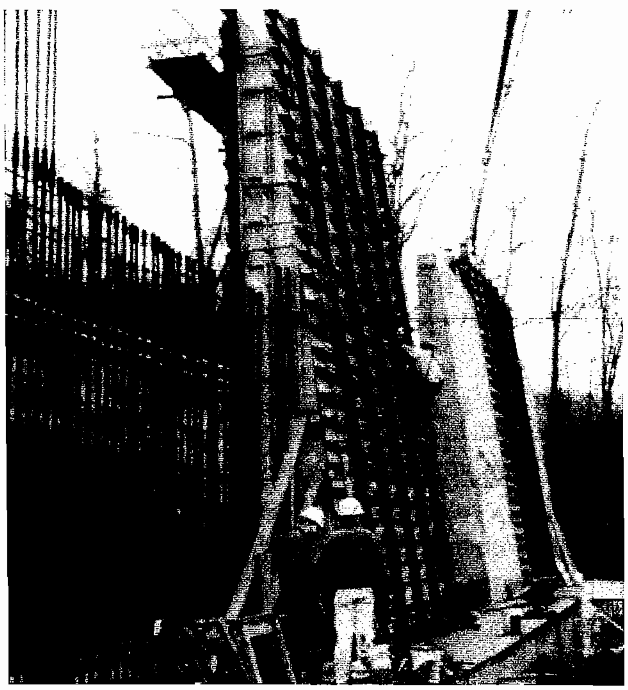


Figure 5. Formwork and reinforcing steel for wall stem of cantilever wall.

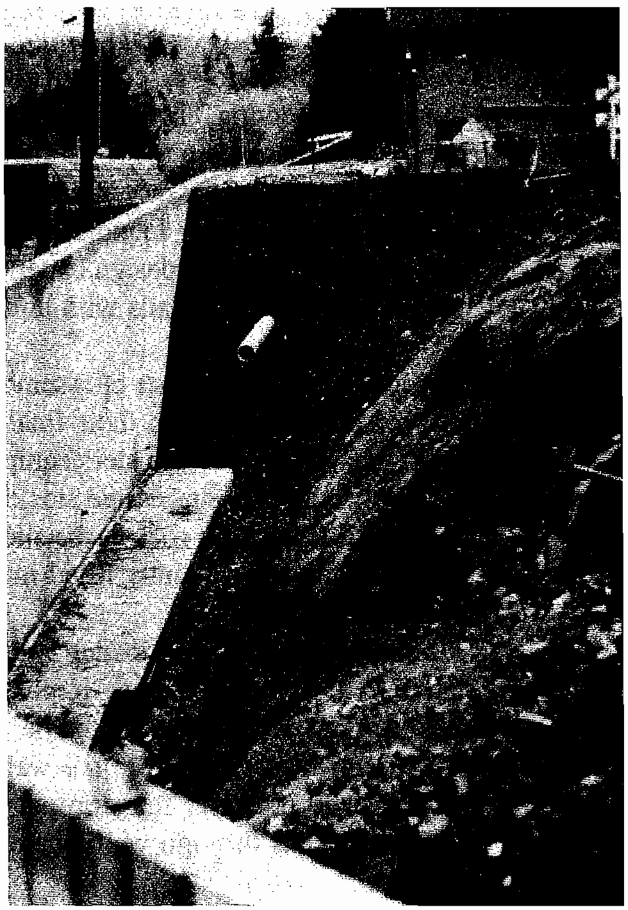


Figure 6. Cross-sectional view of cantilever wall showing drain pipe.

3.2.3 Prefabricated Modular Gravity Walls

Prefabricated modular gravity walls are constructed from either precast concrete, steel, or timber units. Bin or crib type walls are assembled on-site from prefabricated precast concrete, steel, or timber members (stringers and spacers) to form rectangular or square enclosures that are then backfilled. Alternatively, the bins or cribs may be self-standing precast concrete units with standard heights and face widths and variable lengths. The units are "stacked" on each other and backfilled progressively in lifts. A gabion wall is a prefabricated modular gravity wall that is constructed from preformed wire baskets filled with clean rock.

The sequence of construction for prefabricated modular gravity walls is described below.

- Excavation to the wall foundation grade, foundation preparation, and construction of temporary excavation support are performed similarly to that for rigid gravity and semi-gravity walls.

- Typically, walls using discrete stringers and spacers, which are field assembled, do not require a wall footing. In contrast, precast concrete units are erected on small longitudinal footings supporting both the front and back face of the units. The purpose of these footings is to provide the necessary erection tolerances and, for some proprietary systems, to transmit the load to the foundation. For walls designed with a front batter, the footing surface is inclined at the design batter angle. Wall alignment should be checked frequently, especially for battered walls with horizontal curves.

- Erection of the wall consists of assembling the stringers (longitudinal members) and spacers (transverse members) into their final square or rectangular geometry. For fully precast bins, cranes or front end loaders equipped with slings are used to unload the bins and erect the wall through the successive stacking of units on top of each other. For gabion walls, the units are filled with rock at the site either in-place or the units are constructed adjacent to the wall and subsequently lifted into place.

- A clam shell or front end loader is used to place the backfill within each enclosure. The backfill is then hand spread, if possible, and compacted with portable vibratory plate tampers. The backfill used should be a select fill. For open-faced units, the backfill surface should be graded away from the wall face at the end of each day of construction. This minimizes the potential for stormwater to penetrate into the wall backfill and wash out backfill materials through wall face openings.

Figures 7 through 11 illustrate some of the stages of construction for various prefabricated modular gravity walls.

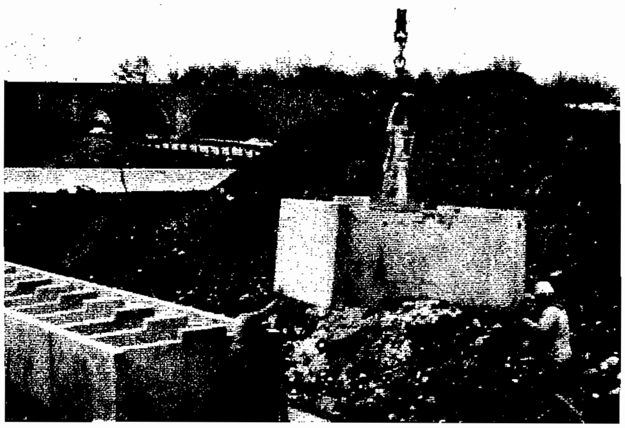


Figure 7. Erection of first course for a concrete bin wall.

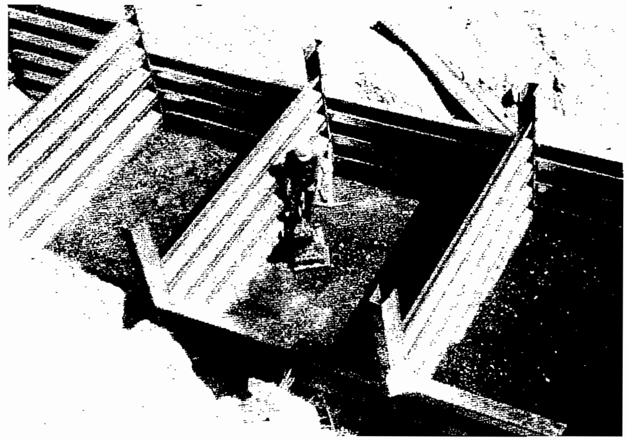


Figure 9. Compaction within metal bin wall module.

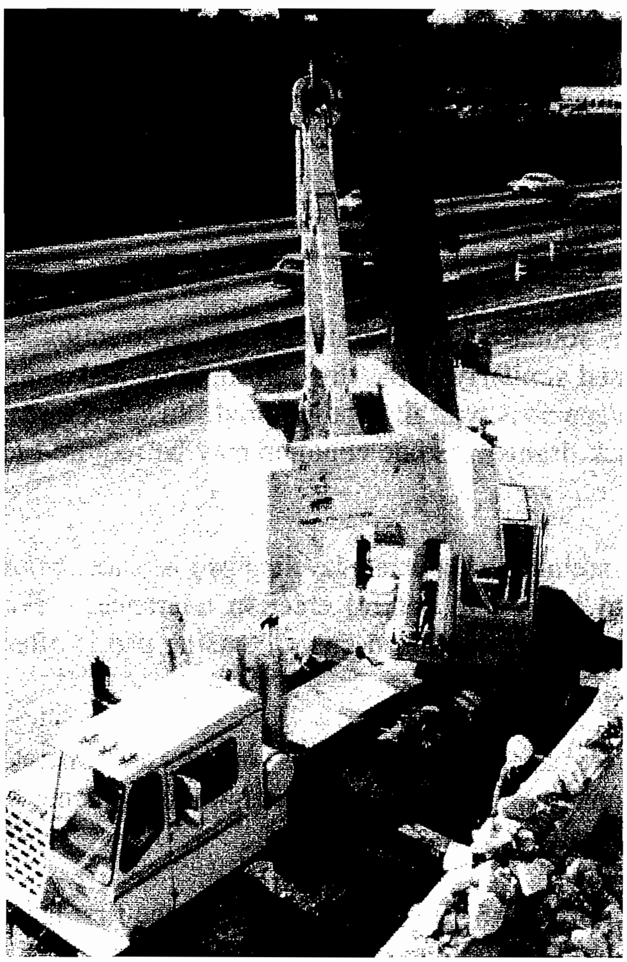


Figure 8. Erection of subsequent courses for a concrete bin wall


Figure 10. Erection of spacers and stringers for metal bin wall.

Figure 11. Erection of gabion wall.

3.2.4 Mechanically Stabilized Earth (MSE) Walls and Reinforced Soil Slopes (RSS)

All MSE wall systems with precast facing elements use a common construction method. This method involves a step-by-step procedure that is repeated until the full wall is erected. The method differs slightly depending on the type of facing (prefabricated modular panels or blocks versus geosynthetics or welded-wire mesh).

The sequence of construction for MSE wall systems having prefabricated modular panels or blocks is described below.

- Excavation to the wall foundation grade, foundation preparation, and construction of temporary excavation support are performed similarly to that for rigid gravity and semi-gravity walls except additional foundation support is typically not required. In some cases, ground improvement methods such as wick drains or stone columns may be required to meet project specific criteria.

- A small (300-mm wide by 150-mm thick) unreinforced concrete leveling pad is placed prior to erection of the facing units. This pad is used to control erection tolerances. For prefabricated modular block facing MSE walls, a compacted gravel leveling pad is often used in lieu of unreinforced concrete.

- Facing units, which may be precast concrete panels or metal panels, or dry cast concrete modular blocks, are erected. If precast concrete panels are used, temporary bracing is required to maintain stability and alignment.

- Select backfill is placed on the subgrade in one or more lifts to the level of the first layer of reinforcing elements. Prior to placement of the reinforcement, each lift of the backfill is compacted to a specified density with self-propelled compaction equipment operating to within 1 m of the back face of the wall. Smaller vibratory plate tampers are used closer to the back face of the wall to prevent compaction-induced damage or distortion to the facing panels. Frequent surveys should be performed to ensure that appropriate wall alignment is maintained.

- The first layer of reinforcing elements is placed on the compacted backfill and connected to the facing unit. The method of facing/reinforcement connection depends on the specific MSE wall system being constructed. These methods include bolt connections, insertion of a shear bar, or a frictional or mechanical connection for concrete modular block units.

- Select backfill is placed in lifts over the reinforcing elements to the level of the next layer of reinforcement and the backfill is compacted. The backfill should be dumped into the rear or middle of the reinforcements and bladed towards the back face of the wall.

- The sequence of erecting additional facing units, placing reinforcing elements, connecting reinforcing elements to the facing panels, and placing and compacting the select fill in lifts is repeated until the wall reaches the final height.

Figures 12 through 14 illustrate a complete sequence of construction for an MSE wall system with precast facing panels and figures 15 and 16 show typical facing/reinforcement connections for two different MSE wall systems.

Figure 12. Leveling pad for a MSE wall.

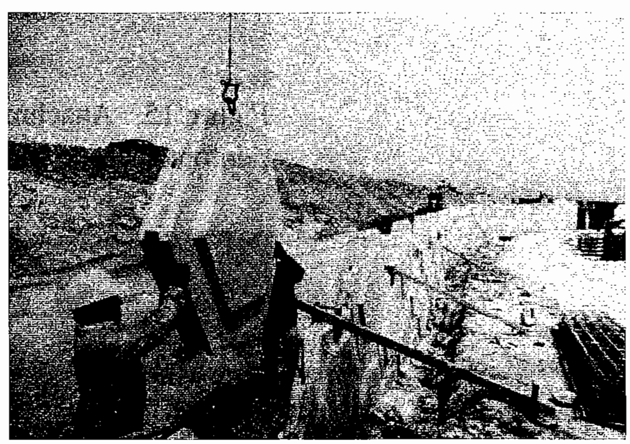


Figure 13. Erection of MSE facing panels.

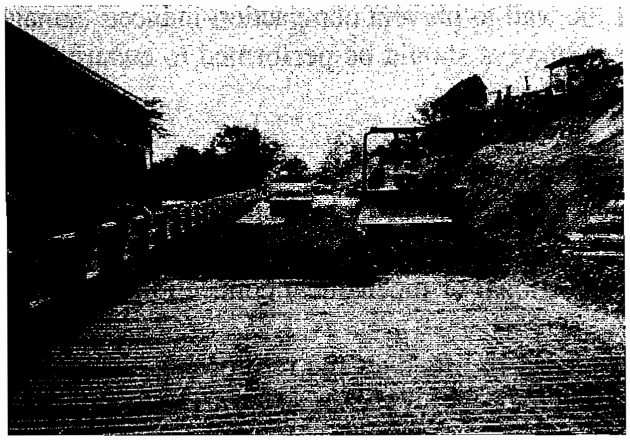


Figure 14. Spreading and compaction of select fill for MSE wall.

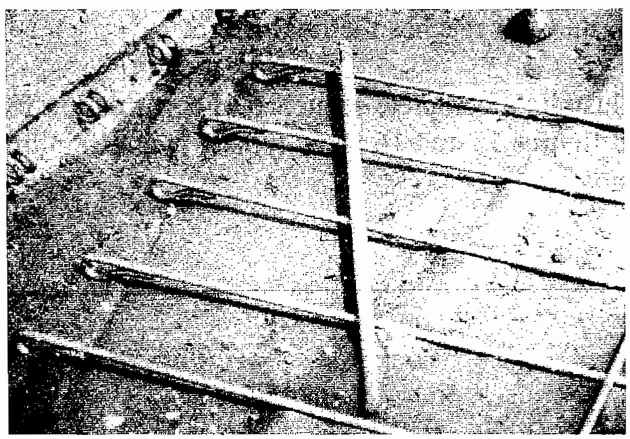


Figure 15. Attachment device for metallic grid reinforcement to MSE facing panels.

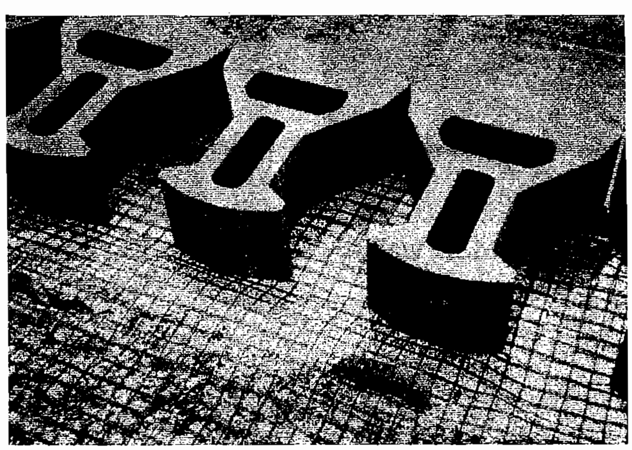


Figure 16. Frictional connection for concrete modular block MSE wall.

The sequence of construction for MSE wall systems which use either geotextile, geogrid, or welded-wire mesh facing is slightly different than described above if the reinforcement is also used as the facing unit. In this case, the facing is formed by wrapping each layer of reinforcement around the overlying layer of backfill (i.e., wrap-around construction). For geotextile and geogrid walls, specialized facing forms are used to construct each lift and to permit compaction of the backfill against the wall face.

The sequence of placing reinforcing elements and placing and compacting fill for a reinforced soil slope is similar to that for a wrap-around MSE wall. RSS, however, can also be constructed with no-wrap construction wherein the reinforcement is terminated at the slope face. The decision to employ either wrap-around or no-wrap construction generally depends on the slope angle. For slope angles less than approximately 45 degrees, no-wrap construction can be used if the reinforcement is placed at close vertical spacing. Alternatively, primary reinforcement can be placed at greater vertical spacing if secondary reinforcement is installed at the slope face between vertical levels of primary reinforcement. If slope facing is required to prevent sloughing or erosion of the soil, several options are available. These include: (1) providing sufficient reinforcement length to permit wrap-around construction; (2) vegetating the slope face; and (3) constructing erosion control mats or prefabricated elements on the slope face. Figure 17 illustrates wrap-around and no-wrap construction for reinforced soil slopes.

3.2.5 Construction Equipment and Materials

Specialized equipment is typically not required for fill wall construction. Earthwork associated with foundation preparation only requires conventional equipment including backhoes and hand-tools. Cranes or front end loaders equipped with slings are used to unload and erect precast concrete crib units and MSE wall facings. Where concrete modular block units are used, only light lifting equipment may be necessary as the typical weight of each block ranges from 35 to 70 kg. Placement and compaction of select fill requires conventional equipment such as bulldozers and vibratory rollers. Within a 1 m zone from the back face of a wall, hand tampers or small self-propelled compactors are used.

Construction and material specifications for fill walls are given in Section 7 of AASHTO (1994), Division II-Construction.

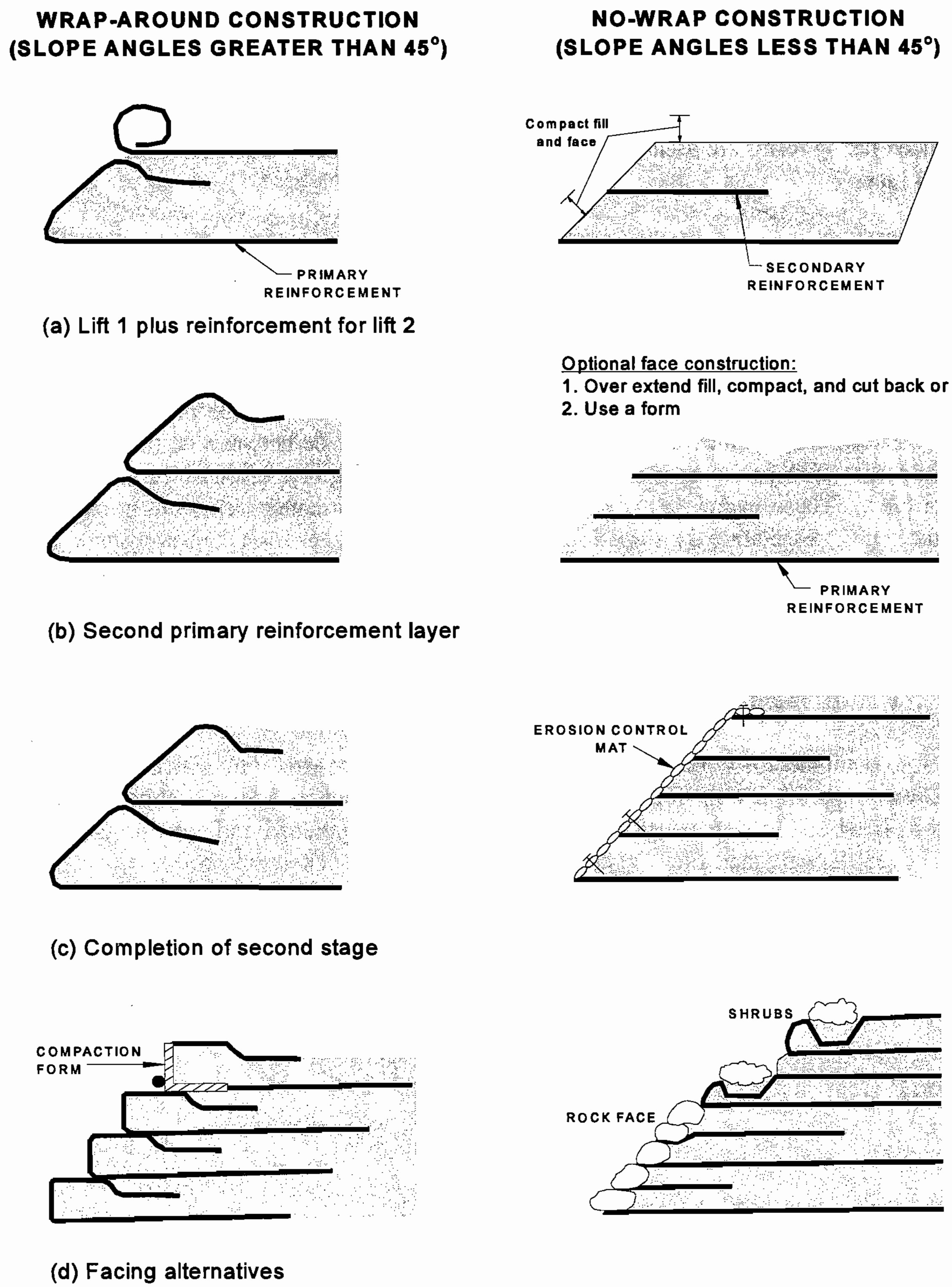


Figure 17. Wrap-around and no-wrap construction for reinforced soil slopes (modified after FHWA-SA-96-071, 1996).

3.3 CUT WALL CONSTRUCTION

3.3.1 General

Cut wall construction is typically employed to provide retention support where construction must proceed from the top-down due to geometric and/or environmental constraints. Cut walls are typically used in applications such as underpass construction.

The methods of construction for cut walls depend on the specific wall type. An overview of the construction materials and procedures for cut wall systems is provided below.

- *Nongravity Cantilevered Walls*: These wall systems employ either discrete (e.g., soldier pile) or continuous (e.g., sheet-pile) vertical wall elements that are either driven or drilled to depths significantly below the finished excavation grade. Support is provided through the shear and bending stiffness of these vertical elements and passive resistance from the soil below the finished excavation grade. Discrete vertical wall elements may consist of steel piles or drilled shafts that are spanned by a structural facing. The facing may be wood lagging, precast concrete, or CIP concrete. Alternatively, the vertical wall elements and facing may be continuous and, therefore, also form the structural facing. Typical continuous wall elements include steel sheet-piles, CIP concrete slurry (diaphragm) wall panels, tangent/secant piles, and soil-cement columns.

- *Anchored Walls*: These wall systems are composed of the same elements as nongravity cantilevered walls, but obtain additional horizontal support from one or more tiers of ground anchors (tiebacks). Anchors may be prestressed elements (usually strand steel or bars) with appropriate corrosion protection that extend from the wall face to a grouted zone located significantly behind the wall face.

- *Soil-Nailed Walls*: These wall systems consist of a reinforced shotcrete face constructed incrementally from the top-down. An array of relatively closely spaced (1 to 1.5 m) nails are placed in drilled holes through the facing which are subsequently grouted. For permanent walls, shotcrete, CIP concrete facing, or prefabricated precast concrete panels can be subsequently constructed on or in front of the shotcreted face.

- *Micropile Walls*: These wall systems consist of an array of micropiles that are installed from the ground surface to an underlying strata that is below a potential sliding surface. This type of construction does not form a visible wall and is often used to stabilize unstable slopes.

The need for drainage for cut wall systems depends on the specific project requirements. For some applications, a watertight wall may be required and a drainage system is, therefore, not required. This situation may occur when surrounding ground water is contaminated, when ground-water drawdown may induce settlements in nearby structures, or when it is necessary to maintain a "dry" excavation. In other cases, drainage measures may be needed to: (1) reduce water pressures and freezing water pressures from acting on the back of the wall; (2) protect facing elements from potential deterioration induced by contact with water; and (3) prevent saturation of the retained soil mass (Foundation Engineering Handbook, Chapter 26, 1991). Drainage is usually achieved, where needed, by installation of drainage media immediately behind the wall facing and/or by drilling horizontal drains into the retained soil mass at an appropriate stage of construction.

3.3.2 Nongravity Cantilevered Walls

3.3.2.1 Soldier Pile and Lagging Wall

The sequence of construction for soldier pile and lagging walls is described below.

- The initial step of construction consists of installing the soldier piles from the surface to their final design elevation. Horizontal spacing of the soldier piles typically varies from 2 to 3 m with a common spacing being 2.4 m. The soldier piles may be steel H beams or drilled shafts. Steel H beams are normally driven using pile driving equipment and drilled shafts are constructed by drilling and subsequently concreting the shaft.

- The next phase of construction consists of excavation at the wall face in 200- to 500-mm deep increments, followed by the installation of wood or concrete lagging between the flanges of the H beams. Lagging should be placed as soon as possible after excavation to minimize erosion of materials into the excavation. Where drilled shafts are utilized, the incrementally excavated face is often initially shotcreted for temporary support and then permanently faced with CIP or precast concrete panels suitably connected to the drilled shaft.

Figure 18 shows the installation of a soldier pile, and figure 19 shows the installation of wood lagging between steel H beam soldier piles.

3.3.2.2 Sheet-Pile, Tangent Pile, and Secant Pile Walls

The sequence of construction for sheet-pile, tangent pile, and secant pile walls is described below.

- Sheet-pile walls are constructed in one phase in which interlocking sheet-piles are driven to the final design elevation using pile driving equipment. Where difficult driving conditions are encountered, a template is often utilized to achieve proper longitudinal alignment of the sheet-piles. Interlocking sheet-piles may be either steel or precast concrete. Steel sheet-piles are normally used for temporary applications as they are typically more readily available and stronger than precast concrete sheet-piles.

Figure 18. Driving soldier piles.

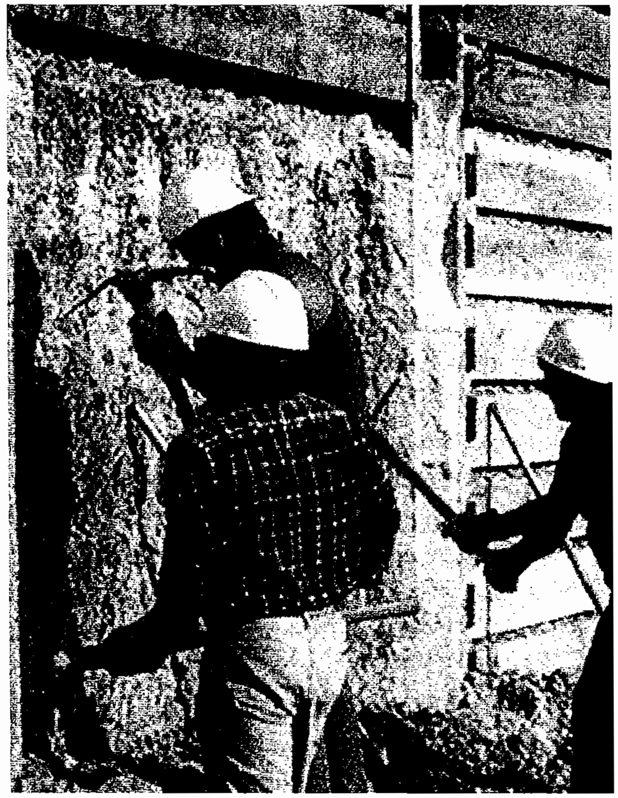


Figure 19. Installation of wood lagging.

Alternatively, drilled shafts, cased or uncased as necessary, are drilled in a secant or tangent layout to the final design elevation. The required reinforcement is lowered into the shaft and the shaft is then concreted using an appropriate method.

- Excavation then proceeds to finished grade in front of the wall. If a uniform planar wall finish is required, the front face can be covered with CIP or precast concrete panels.

Figure 20 shows a steel sheet-pile being driven and figure 21 shows a completed tangent pile wall.

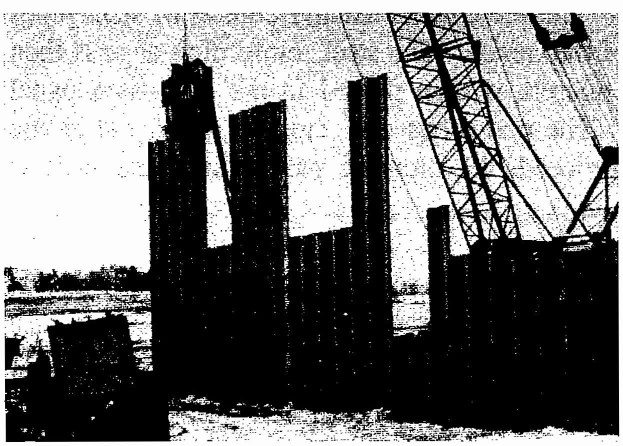


Figure 20. Typical sheet-pile installation.

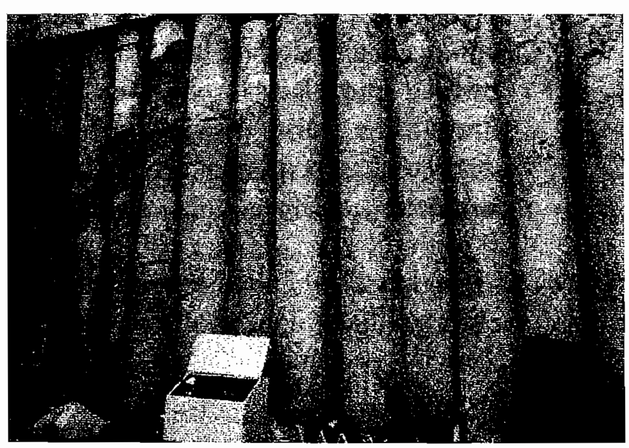


Figure 21. Completed tangent pile wall.

3.3.2.3 Slurry (Diaphragm) Walls

A slurry (diaphragm) wall is constructed within a narrow trench that has been excavated to the full wall depth. The trench is stabilized with a mineral or polymer slurry as the excavation proceeds. The wall is constructed by placing the structural elements into the trench from the ground surface.

The sequence of construction for slurry (diaphragm) walls is described below.

- The initial step of construction consists of installing two 1.0- to 2.0-m, high guide walls at the ground surface along the edges of the trench alignment. The guide walls usually consist of 150- to 250-mm thick CIP or precast reinforced concrete elements. The guide walls serve to support the ground at the surface, guide the trench excavation equipment, support the reinforcing steel cage during concrete placement, and protect the top edge of the trench as the equipment is lowered and raised. The width of the trench, which is also the width of the completed wall, is usually between 0.4 and 1 m. Care must be taken in constructing the guidewalls as horizontal and vertical construction controls such as wall alignment and wall verticality are based on measurements which are referenced to the guidewalls.

- Soil is excavated from the trench using a backhoe (for trench depths less than 7 m), a hydraulic clamshell bucket (figure 22), or, for difficult excavation through soil and rock, a reverse circulation boring unit. The latter unit is suspended from a crane and consists of a heavy metal frame at the base of which are two counter-rotating drums with teeth. The most widely used unit of this type is known as a hydromill (figure 23). After an individual panel (primary panel) is excavated, the sediments in the suspended slurry are removed using a pump centrally mounted within the unit and a desanding process. The desanded slurry is reused for the construction of subsequent panels.

- Temporary end tubes or end stops are lowered into place at both ends of the excavated panel to provide a form for concrete placement. These elements usually consist of steel pipes with diameters slightly less than the width of the trench. The steel reinforcing cage is then lowered into place through the slurry. Concrete is then placed in the excavated panel through the slurry using tremie methods. The end tubes are removed slowly after the concrete has begun to set. Concreting proceeds in alternate panels until the wall is complete.

Figures 24 through 27 illustrate several stages of construction and some of the types of equipment utilized for slurry (diaphragm) wall construction.

Figure 22. Conventional grab bucket for slurry (diaphragm) wall construction.

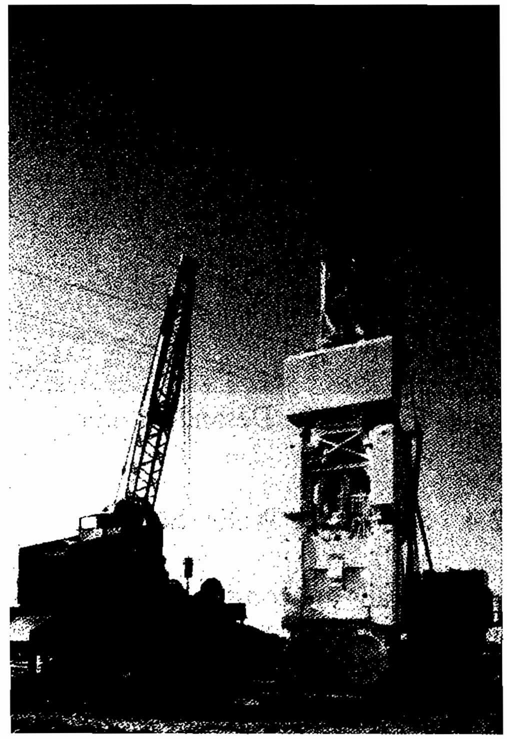


Figure 23. Hydromill for slurry (diaphragm) wall construction.

Figure 24. Guide wall construction.

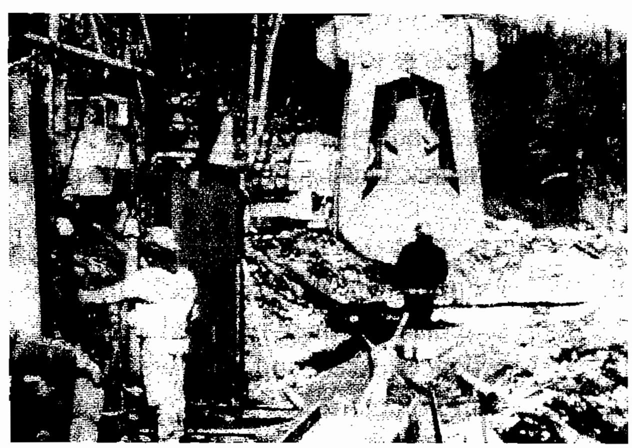


Figure 25. Hydraulic clam shell for excavation.

Figure 26. Desanding unit.

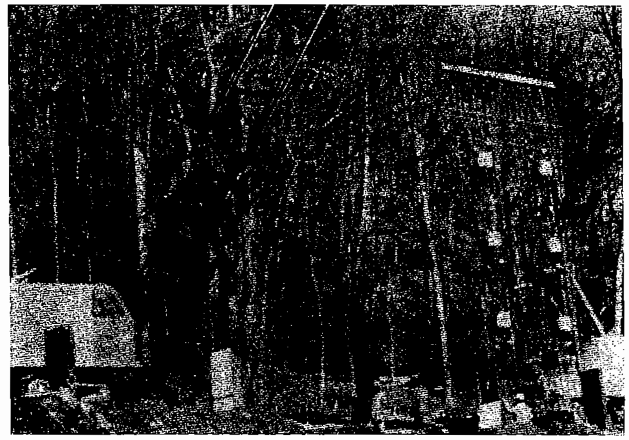


Figure 27. Lowering steel reinforcement cage into slurry trench.

3.3.2.4 Soil Mixed Walls (SMWs)

Soil mixed walls are constructed in-situ using specialized auger equipment. The equipment typically consists of a number of mixing augers mounted in a side-by-side arrangement with overlaps between adjacent augers. As the mixing augers are advanced into the soil, cement grout is pumped through the auger shafts and injected into the soil at the tip of the augers or through the mixing blades of the augers. During insertion, the soil and the grout are continuously mixed. The mixing process is repeated during auger withdrawal. A panel of overlapping soil cement columns remains in place after mixing is completed. These overlapping columns form a soil-cement wall after adequate curing.

The sequence of construction for soil mixed walls (SMWs) is described below and is shown schematically in figure 28.

- A three- to five-hole pattern is drilled to form a primary panel. Upon completion of this primary panel, the equipment is moved along the alignment of the wall to the appropriate position for constructing the next primary panel. This primary panel is then constructed similarly to the first primary panel.

- A secondary panel is then constructed to span the interval between the two adjacent primary panels. This secondary panel is positioned to establish wall continuity.

- The final step consists of installing structural members such as H beams or steel pipes, as required for reinforcement, into the soil cement columns prior to curing. The above sequence is then repeated until the soil mixed wall is completed. Wall construction produces excess soil spoil with a volume of approximately 20 to 30 percent of the completed wall volume.

The equipment used in constructing this wall system is shown in figures 29 and 30.

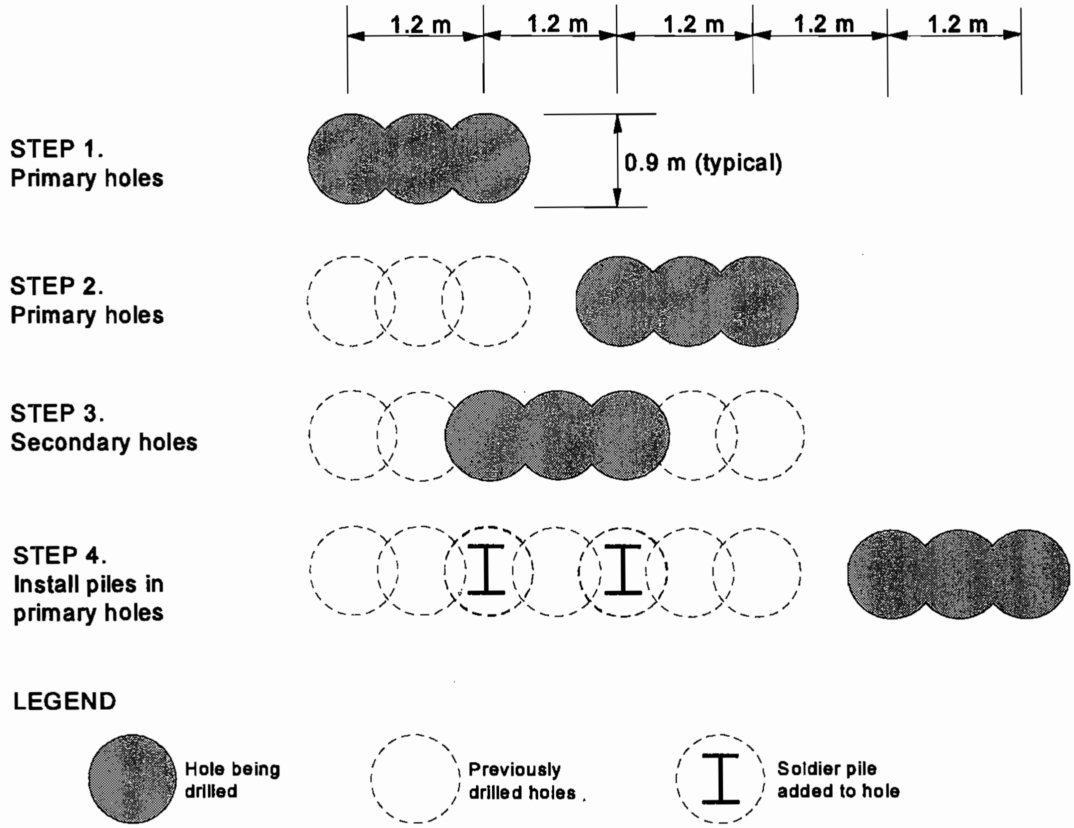


Figure 28. Construction sequence for soil mixed walls (modified after Pearlman and Himick, 1993, Anchored Excavation Support Using SMW, Deep Foundations Institute (DFI). Reprinted by permission of DFI).

Figure 29. Mixing equipment for soil mixed wall.

Figure 30. Mixing of soil cement.

3.3.2.5 Construction Equipment, Methods, and Materials

A variety of equipment and methods are utilized for nongravity cantilevered wall construction. The type of equipment used depends on the type of wall system to be constructed. For the installation of steel H beams and sheet-piles, conventional pile driving equipment is used. For tangent/secant drilled shaft construction, suitable drilled shaft equipment is utilized. For slurry (diaphragm) wall construction, specially constructed hydraulic clam shells or hydromills. A desander unit or settling pond must be provided with ultimate disposal volumes for excavated soil being approximately equal to the volume of the completed wall. For soil mixed walls (SMW), proprietary multiple-flight auger units suspended from crawler crane booms are used, and provisions must be made for spoil disposal.

Construction and material specifications for non-gravity cantilevered wall systems are contained in the following sections of AASHTO (1994), Division II - Construction:

- Section 4 (driven piles);
- Section 5 (drilled shafts); and
- Section 7.6.2 (sheet-pile and soldier pile walls).

Standard industry construction and material specifications are not yet available for slurry (diaphragm) walls and soil mixed walls. Additional information on slurry (diaphragm) wall construction, materials, and construction quality control can be found in ASTM (1992).

3.3.3 Anchored Walls

3.3.3.1 General

Anchored wall construction is similar to that for non-gravity cantilevered walls, except that construction of this type of wall also involves installation of ground anchors (tiebacks) or deadman anchors. The significant construction characteristics associated with ground anchors are placement, proof testing, and lock off of a predetermined, prestressed anchor load to a structural member at the wall face.

A ground anchor is a structural system that is used to secure a tendon that applies a force to the structure. The major components of a ground anchor are shown schematically in figure 31. The tendon is composed of a steel rod, or cable, with sheathing and an anchorage. The ground anchor transmits the tendon force into the soil well behind the wall face; the anchor bond zone (anchor length) extends behind any potential active soil wedge that stresses the wall face. The anchorage is made up of an anchor head or nut and a bearing plate that provides the load transfer mechanism to the structure.

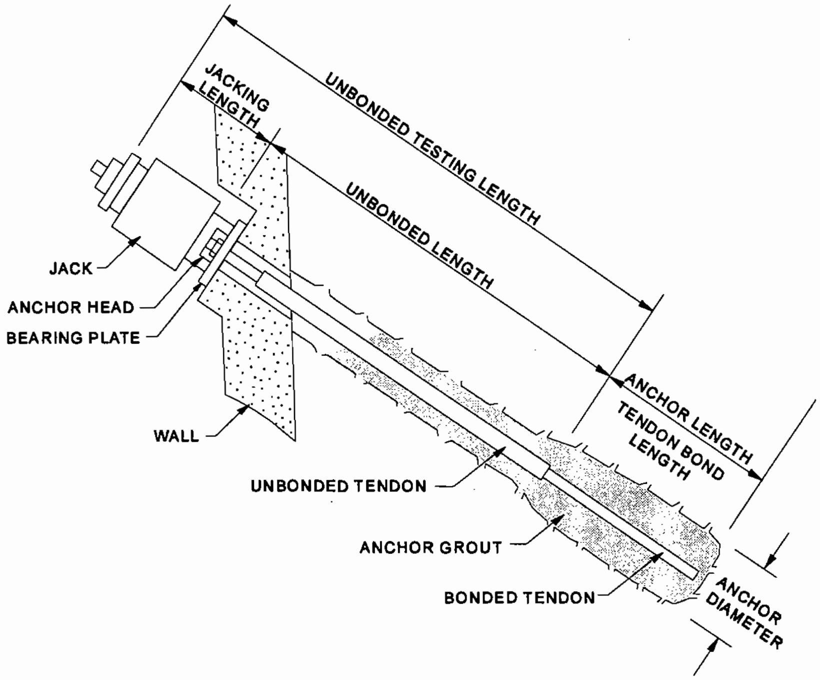


Figure 31. Components of a ground anchor (modified after FHWA-RD-82-047, 1982).

3.3.3.2 Construction Sequence

The construction sequence for anchored walls is the same as that for nongravity cantilevered walls until excavation reaches approximately 1.0 m below the location of each ground anchor. At this stage of construction, a ground anchor is installed. Ground anchors can be installed by a variety of drilling and grouting procedures. The procedures used for any particular project are often chosen based on local experience and contractor preference. Common methods of drilling and grouting, as well as anchor corrosion protection and anchor proof testing, are described in subsequent subsections.

3.3.3.3 Ground Anchor Installation

Straight Shaft Ground Anchors Using Low Grout Pressure

This type of ground anchor is typically installed in rock or soil using either rotary drilling or hollow-stem augers. Grouting is achieved either by low pressure injection (grouting pressures less than 1 MPa) or by gravity tremie methods.

When rotary drilling is used, the drill hole is made by rotating a casing into the soil and periodically cleaning out the soil plug with drag or roller bits and water or air flushing. Where soil conditions allow, the hole may be drilled without casing. When casing is used, the hole is drilled, cleaned and tremie grouted, and the tendon is then inserted through the grout to the bottom of the hole. The casing is reconnected to the drill and additional grout is pumped during extraction. If no casing is employed, the hole is tremie grouted along its entire length and then the tendon is inserted.

The drill hole for ground anchors can also be made using a continuous flight, hollow-stem auger. With this method, the tendon is inserted in the auger prior to drilling. The tendon is equipped with a locking device that allows the tendon to be advanced into the soil with the auger, but which leaves the tendon in place in the soil when the auger is withdrawn. The auger is positioned and the hole is drilled. As the auger is extracted, grout is pumped down the hole.

Pressure Injected Ground Anchors

This type of ground anchor is typically installed in sandy or gravelly soils using a driven or drilled casing. With this type of anchor, grouting pressures are in excess of 1 MPa. After the casing is installed, the tendon is fitted with a closure point or drag bit and then inserted down the hole inside the casing. The casing is then extracted a short distance using centerhole hydraulic jacks and the tendon is driven into the soil at the bottom of the drill hole. Grout is then pumped down the casing under pressure while the casing is extracted until the entire anchor bond length is grouted.

Postgrouted Ground Anchors

Postgrouted ground anchors are used primarily in cohesive soils. Postgrouting is used to enlarge the grout bulb located within the anchor bond length. This is done by making supplemental grout injections into the initially grouted anchor bulb. The time period between each supplemental injection is approximately 1 day. This technique is intended to fracture the grout already in place and wedge it outward into the soil. The method requires that a special grout tube with valves located along the anchor length (tube à manchette) be placed in the drill hole along with the tendon. The grout tube is designed so that a double packer can be used inside the tube to selectively grout each section with a predetermined volume of grout. As many as three or four periodic grout injections may be used for anchor installation in cohesive soils.

Centralizers and Spacers

Centralizers and spacers are placed along the anchor bond length at a typical maximum spacing of 3 m. Centralizers enable the tendon to be positioned in the drill hole such that the specified minimum grout cover is achieved around the tendon. For multiple element tendons, spacers are used to separate the wires, strands, or bars of the tendons so that each element is adequately bonded to the anchor grout.

Rotary and auger drilling equipment used for installation of ground anchors is shown in figures 32 and 33. Several completed anchor walls are shown in figures 34 through 36.

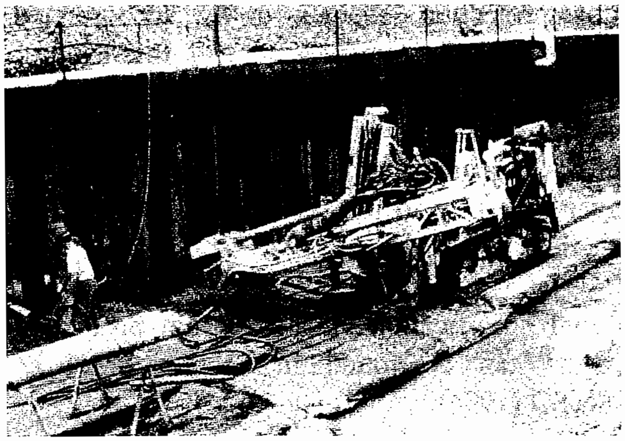


Figure 32. Rotary drilling equipment for ground anchor installation.

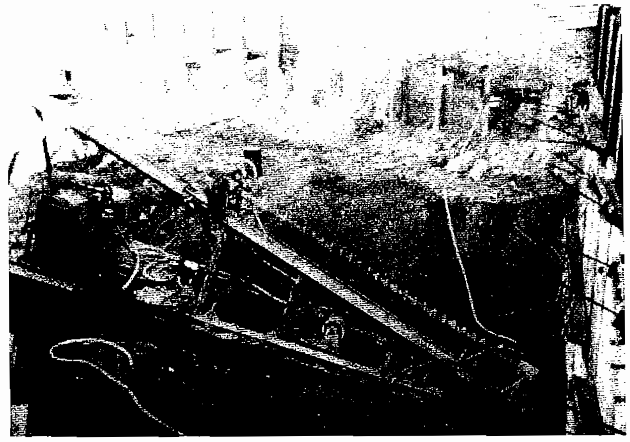


Figure 33. Auger drilling equipment for ground anchor installation.

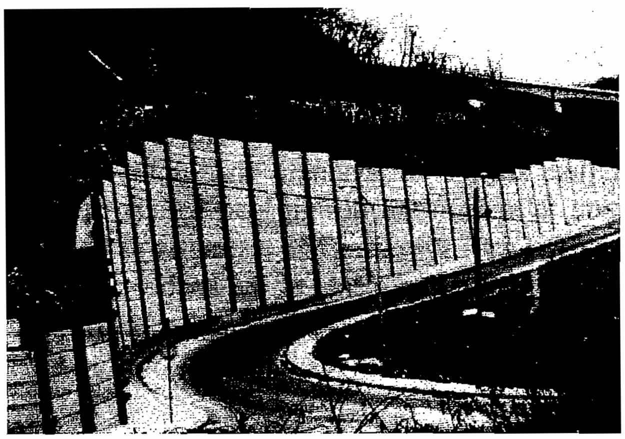


Figure 34. Anchored wall with precast concrete lagging (ground anchors connected at soldier piles)

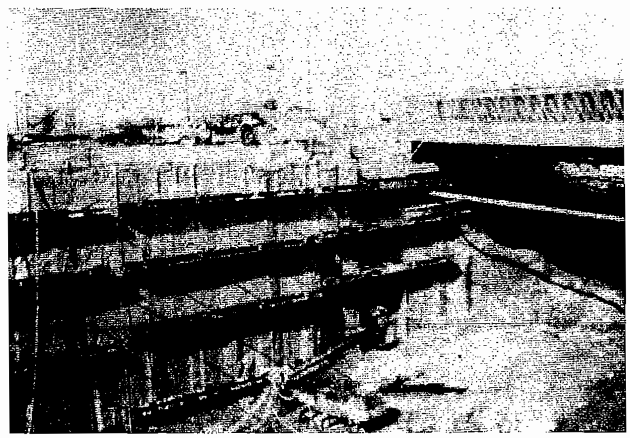


Figure 35. Anchored soil mixed wall (ground anchors connected at walers)

3.3.3.4 Corrosion Protection of Ground Anchors

Ground anchors for permanent earth retaining wall applications require corrosion protection. This is achieved by the application of one or more levels of protection depending on the criticality of the wall, the aggressiveness of the soil and ground-water regime, the cost of the protection measure, and the design life of the wall.

Single protection schemes rely on the cement grout to protect the anchor tendon, bar, or strand in the anchor bond length. The unbonded length is protected by methods which include the use of smooth sheaths filled with anti-corrosion grease, heat shrink sleeves, and/or secondary grouting of the unbonded length after the anchor has been stressed.

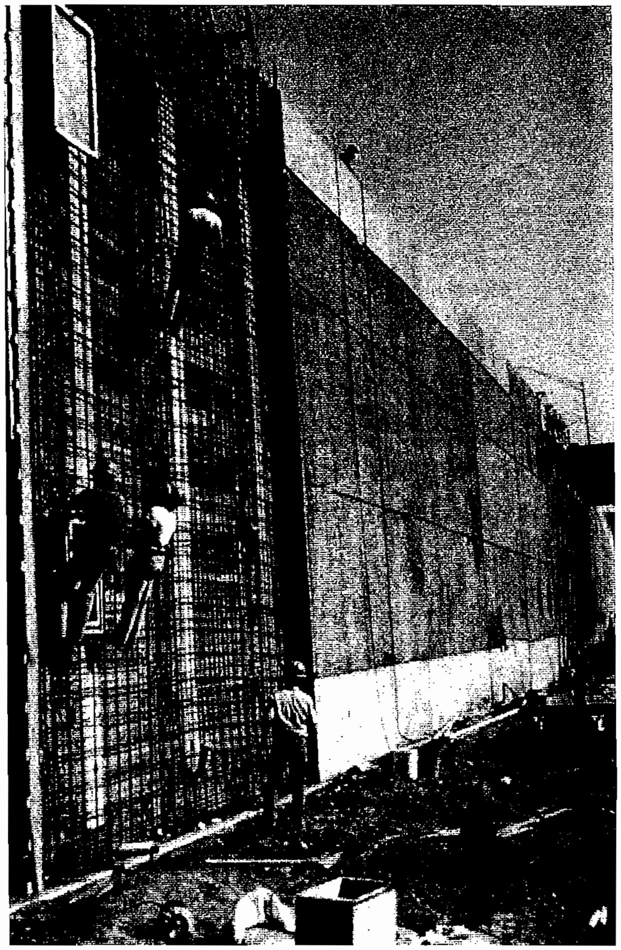


Figure 36. CIP permanent facing being constructed on an anchored wall.

Double protection schemes for the anchor bond length involve the cement grout as a first level of protection, and complete coverage of the cement grout with a plastic or steel tube as the second level. Alternately, the tendon can be coated with a layer of epoxy to provide the second level of protection.

Material specifications for corrosion protection elements can be found in Section 6.3.4 of AASHTO (1994).

3.3.3.5 Testing and Load Transfer of Ground Anchors

Ground anchor load testing is performed on each installed anchor to evaluate the ability of the system to sustain the design load for the service life of the wall system. The testing is performed by loading all components of the anchor to above the design load, thus providing a basis for acceptance of the entire anchor.

Each anchor is tested either by a performance test or a proof test. Typically, 5 percent of the anchors are performance tested, and the remaining anchors are proof tested. In a proof test, the anchor is incrementally loaded up to approximately 133 percent of the design load. At each load increment the movement of the anchor is recorded and evaluated. In a performance test, the maximum anchor load is approximately the same as that in a proof test, but loading and unloading increments will be used and loading durations will be greater. Both performance and proof tests are used to evaluate anchor capacity and likely permanent deformation.

After the design load of a ground anchor has been verified by testing, the required load is transferred from the testing jack used in either the proof or performance test to the structure. This load, termed the "lock-off load," may be smaller than the design load.

A typical set up for a ground anchor proof test is shown in figure 37.

Figure 37. Load testing and stressing setup for a ground anchor proof test.

3.3.3.6 Construction Equipment, Methods, and Materials

Equipment and materials for the construction of anchored walls are the same as that for non-gravity cantilevered walls and specific requirements depend on the type of vertical wall element to be constructed. For the installation of ground anchors, auger or rotary drilling methods and equipment is typically used. For grouting, combination drilling and grouting rigs developed especially for anchor installation are often used.

Construction and material specifications for ground anchor construction are contained in AASHTO (1994), Division II - Construction, Section 6; AASHTO-AGC-ARTBA Task Force 27 (1990); and FHWA DP-68-1R (1988). Recommendations for ground anchors utilizing high strength steel can be found in PTI (1995).

3.3.4 Soil-Nailed Walls

3.3.4.1 General

Soil nailing is an in-situ reinforcement technique wherein nails are inserted into a soil mass to reinforce the soil. The installation of soil nails differs from that of tieback anchors in that soil nails are passive inclusions (i.e., unlike ground anchors, soil nails are not post-tensioned). Also, soil nails are more closely spaced than ground anchors. Soil-nailed walls are built from the top-down in incremental construction lifts. The construction of each lift includes excavation, nail installation, and shotcreting of the excavated face.

3.3.4.2 Construction Sequence

The sequence of construction for soil-nailed walls is described below.

- An initial excavation in the soil is made to a specified depth. This excavation depth is governed by the ability of the soil to stand unsupported, but is no greater than the required vertical spacing of the nails. The initial excavation depth may also be controlled by the allowable cantilever span of the temporary shotcrete facing above the first row of nails.

- Prefabricated drainage strips are placed and then the exposed excavated soil face is covered with a steel mesh-reinforced shotcrete layer. If the excavated face has sufficient stand-up time, nails can be installed before the exposed excavated soil face is shotcreted.

- Nails of specified length and inclination are installed at predetermined locations. A method of drilling is used that is appropriate for the in-situ soil type. Typical installation methods include rotary and auger drilling. Drill holes constructed using rotary drilling equipment range in diameter from 90 to 120 mm, while for auger drilling, drill hole diameters range from 150 to 300 mm. Usually, the nails are standard reinforcing bars with typical diameters of 25 to 35 mm. Nails are usually fitted with centralizers at 3- to 4-m intervals. Tremie grouting is used to complete nail construction and a plate and nut are used to lock the nail to the shotcrete face.

- This sequence is repeated until the final excavated grade is reached.

- For permanent wall applications, a CIP or precast concrete facing or other type of facing is connected to the complete shotcreted structure. Various connection methods are used depending on the facing type and expected loadings.

Soil nails are tested to verify that the nail design loads can be carried without excessive movement and with an adequate factor of safety for the service life of the structure. In addition, testing is usedto verify contractor's drilling, installation, and grouting operations. The frequency of nail testing will vary depending on the size of the project and the variability of the retained soils (FHWA-SA-93-068,1994). Figures 38 through 43 show the sequence of construction for soil-nailed walls.

Figure 38. Excavation of first lift and placement of drainage strips for a soil-nailed wall.

Figure 39. Drilling for a soil nail.

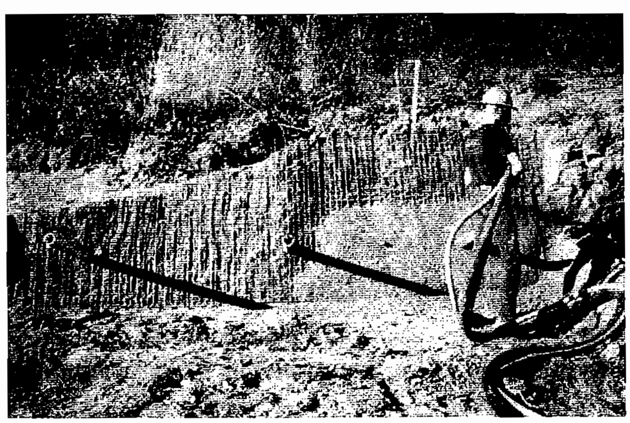


Figure 40. Shotcreting of excavated face.

Figure 41. Grouting of soil nail.

Figure 42. Steel placement prior to second stage of shotcreting.

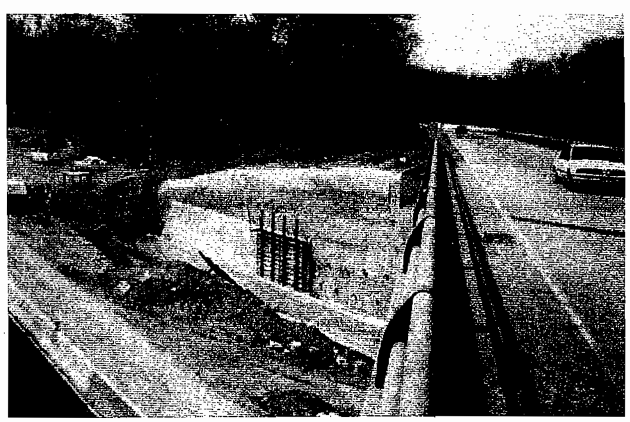


Figure 43. Construction of CIP permanent facing.

3.3.4.3 Construction Equipment and Materials

Construction of soil nailed walls requires either auger or rotary drilling equipment for nail installation. A grout/shotcrete plant is required to mix both the nail grout and the shotcrete. Shotcrete is normally pumped and applied through a high pressure nozzle, while the nail grout is tremied in the hole by gravity. The excavation face is cut by any suitable excavation machinery and requires considerable operator care to minimize overexcavation.

Construction and material specifications for soil-nailed walls are contained in FHWA-SA-93-068 (1994) and FHWA-SA-96-069 (1996).

3.3.5 Micropile Walls

3.3.5.1 General

The construction of this wall system consists of the installation, from the surface, of a relatively closely spaced array of micropiles to a competent underlying strata. Micropile arrays may be installed in a crisscrossing pattern (root-pile walls) or in a combination of vertical and batter orientations (Insert Walls^{SM}). The construction sequence for both of these systems is generally the same.

3.3.5.2 Construction Sequence

The sequence of construction for micropile walls is described below.

- A steel reinforced, CIP concrete cap beam that spans and anchors the micropile array is constructed at the ground surface. The concrete cap beam is typically 2 m wide by 1 m deep. Short corrugated polyethylene sleeves are cast through the cap beam at appropriate locations and inclinations for each of the micropiles. The cap beam concrete is then poured.

- Drilling equipment is aligned in the sleeves and then holes are drilled into the subsurface for the micropiles. Rotary drilling techniques are typically used. Once the casing has been advanced to the final depth, the hole is tremie grouted. The diameter of the micropiles is typically between 130 and 200 mm.

- The micropile, which consists of a reinforcing bar (typically 25 to 50 mm in diameter) or a steel pipe of suitable dimensions, is inserted into the drill hole and then pressure grouted in place as the casing is removed.

Figure 44 shows the stages of construction for a commercially-available micropile wall system.

3.3.5.3 Construction Equipment, Methods, and Materials

Conventional rotary drilling and low pressure grouting equipment is used for the drilling and installation of micropiles for these two wall systems. Construction and material specifications for micropile wall systems can be found in FHWA-RD-96-016 (1997).

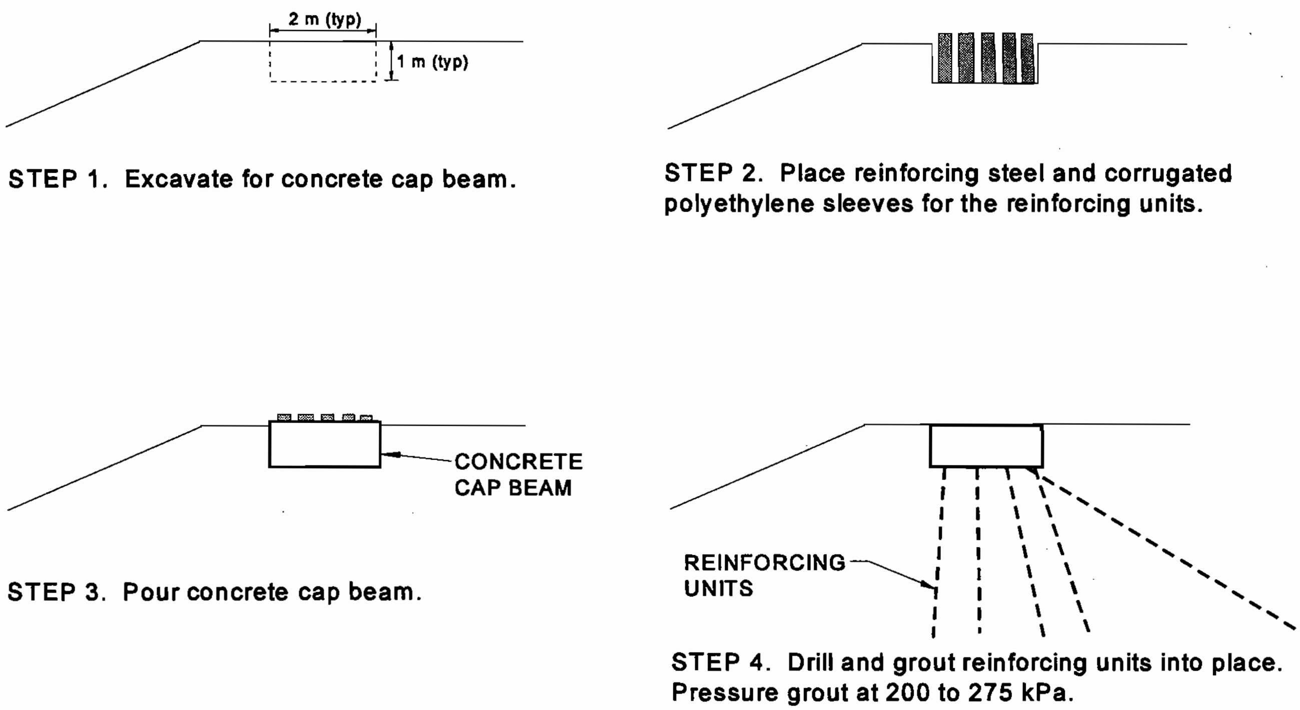


Figure 44. Construction sequence for Insert Wall^{SM} (modified after Bruce, 1992, Two New Specialty Geotechnical Processes for Slope Stabilization, Geotechnical Special Publication No. 31. Reprinted by permission of ASCE).

CHAPTER 4

SELECTION OF EARTH RETAINING SYSTEMS

4.1 INTRODUCTION

An earth retaining system for a highway project application should be cost-effective, practical to construct, stable, and aesthetically and environmentally consistent with its surroundings. These objectives can be accomplished if well-defined formal review and acceptance procedures are employed by an owner agency for wall system evaluation and selection. Through systematic evaluation of all feasible wall systems, the most appropriate wall system can be selected and the maximum potential for cost savings can be realized. In this chapter, the key factors related to the selection process are discussed and the importance of each factor is explained. This chapter also provides general guidance on the selection of earth retaining systems for fill and cut wall applications. The remainder of this chapter is organized as described below.

- Wall system selection is described in section 4.2. This section includes discussion of factors commonly considered in the evaluation and selection of wall systems. In addition, a selection flowchart provides a concise and logical methodology for evaluating and selecting wall systems for a specific project application.

- Wall system selection summary charts are presented in section 4.3. Separate charts are presented for fill and cut wall systems. Each chart presents specific information related to cost, wall geometry, and wall performance. Each chart also includes a summary of advantages and disadvantages of each system related to wall constructability, aesthetics, and environmental requirements.

- The evaluation and selection of technically feasible fill wall and cut wall systems is illustrated through two project examples in section 4.4. Each example begins with a description of the project requirements and constraints. The examples then illustrate the application of both the system selection flowchart and the summary charts.

4.2 WALL SYSTEM SELECTION

This section presents a discussion of the factors involved in wall system evaluation and a flowchart illustrating how these factors are considered during the wall system selection process. This flowchart (figure 45) is intended to serve as a guide for highway design and construction specialists for evaluating and selecting wall system alternates for a project application. Aspects of wall selection that are outside the scope of this flowchart, but which may be part of a formal review and acceptance program, include appropriate contracting procedures, review of approved wall system lists by an owner agency, establishment of technical guidelines and criteria by which feasible wall system alternates can be judged, and performance of a life cycle cost analysis for candidate wall systems.

These aspects are generally agency-specific.

The first step in the selection process is to identify the need for an earth retaining system in the specific project application. A decision on the permanency (i.e., temporary wall or permanent wall) of the wall system is made by the owner agency as part of this step. It is important to note, however, that if sufficient right-of-way (ROW) is available, it may be possible to construct stable soil slopes and thus eliminate the need for a wall system.

The second step in selection involves identifying specific site constraints and project requirements. This information can be obtained during a preliminary site review. Items affecting wall selection include, for example: (1) site accessibility and space restrictions that may include limited ROW and headroom, availability of on-site storage for wall materials, access for specialized construction equipment, and restrictions on traffic disruption; (2) location of underground utilities and nearby structures; (3) aesthetic requirements imposed by project surroundings; and (4) environmental concerns that may include local policies concerning construction noise, vibration, and dust, on-site stockpiling and/or transport and disposal of excavated material, discharge of large volumes of water, and encroachment on existing waterways. The relative importance of each of the above items should be assessed for the specific project under consideration so that the more important items are given priority during the selection process.

Based on the preliminary site review, several wall systems may be eliminated from consideration and others may be recommended for further consideration. Also, this review will provide information necessary to develop a subsurface investigation and laboratory testing program that is consistent with the project requirements. This program can be tailored to provide the information required for establishing design parameters for wall systems that are still under consideration.

The remaining wall systems are evaluated during step three of selection. This step first involves development of more detailed requirements and acceptance criteria related to wall cost, design, performance, and construction. For example, ranges of values for allowable differential settlements for a fill wall application or allowable lateral movements for a cut wall application are prescribed. In addition to cost, the following specific factors are evaluated:

- wall system geometry;
- performance requirements;
- constructability issues;
- aesthetic requirements; and
- environmental concerns and requirements.

In evaluating the above factors for each of the remaining candidate wall systems and the costs associated with them, one or more of the remaining wall systems may be eliminated from further consideration. Finally, based on geotechnical information, cost estimates, and project requirements, several wall systems are selected. The owner agency makes recommendations for the selected wall systems, detailed design is carried out (if appropriate based on the contracting method, see chapter 6) and appropriate construction drawings, specifications, and bid documents are prepared. Contracting methods and formal review and acceptance procedures for earth retaining systems are discussed in greater detail in chapter 6.

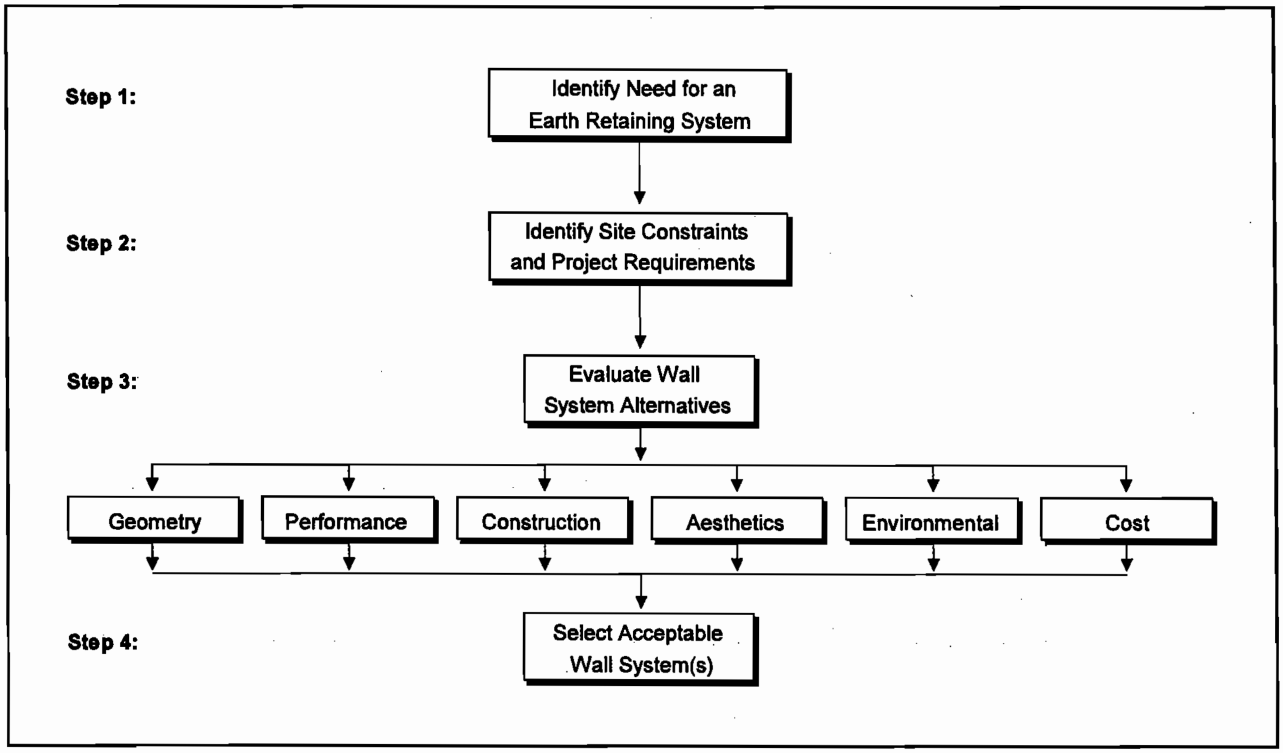


Figure 45. Wall system selection flowchart.

4.3 WALL SYSTEM SELECTION SUMMARY CHARTS

4.3.1 General

Selection charts for fill and cut wall systems are presented in this section. The purpose of these charts is to summarize, in a one-page format, the key selection factors for these categories of wall systems. Separate charts are presented for fill and cut wall systems since key selection factors differ depending on the wall type.

Wall system selection involves an evaluation of candidate systems based on wall geometry, performance, constructability, aesthetic and environmental constraints, and cost. The system selection charts presented herein provide information for each of the wall systems described in the ERS Summaries (chapter 2). These charts condense information from the ERS Summaries to a format that enables convenient comparisons between systems. The reader of this document can use these charts along with the wall system selection flowchart as a framework for the systematic selection of acceptable wall systems on a project-specific basis.

4.3.2 Selection Summary Chart for Fill Walls

The selection summary chart for fill walls (table 3) is presented and discussed in this section. In Section 4.4, this chart is employed to illustrate the selection of a fill wall system for a specific project application.

The design life (i.e., temporary or permanent) for fill wall systems is indicated in table 3. Temporary wall systems typically have a design service life of less than three years. Permanent wall systems are designed for a service life greater than three years and up to 75 to 100 years (AASHTO, 1994) depending on the criticality of the structure. For rigid gravity and semi-gravity walls and prefabricated modular gravity walls, specific provisions for design life are not included in the design calculations and, under normal conditions, these walls are designed for a 75 to 100 year design life. For permanent MSE wall systems and RSS, provisions for the design life are included in the design calculations. For steel reinforcement, loss of reinforcement thickness during the design life resulting from corrosion is calculated and, for geosynthetic reinforcement, time-dependent strength loss (i.e., creep) of the reinforcement is calculated. Design life is normally not a factor for selection of these systems, but for project applications where long-term material durability concerns arise from, for example, exposure to deicing salts, sulfate-rich soils, or frequent freeze-thaw cycles, it may be necessary to include costly protective measures in the design.

As indicated in table 3, all fill wall systems can be used for permanent wall applications. Most of these systems, however, are not typically used for temporary applications due to the high cost of their facing components. For MSE walls with flexible facings and for RSS, however, it is possible to use low-strength, inexpensive, geosynthetic materials for temporary applications as reinforcing-material creep and durability are not major concerns. For walls with metallic components, galvanized components may be employed to provide corrosion protection. This feature may add to the overall cost of the system. For temporary applications, it is cost-effective and technically feasible to fabricate the components without these corrosion protection measures.

Key selection factors related to wall system geometry and cost are also presented in table 3. Typical ranges of values are given for (1) cost-effective height range; (2) cost per square meter of wall face; and (3) required ROW. The lower values for cost and ROW requirements are for low walls and the upper values are for high walls and walls that support sloping backfills or large surcharge loads. In some cases, a significant portion of the cost of a fill wall can be attributed to the cost of the wall backfill. For permanent highway applications, fill wall systems generally require granular, nonplastic, free-draining backfill. The cost effectiveness of a MSE wall system, which typically requires a greater quantity of select backfill than rigid gravity and semi-gravity wall systems, may be reduced if select backfill is unusually expensive at a specific project site.

A performance criterion that is usually prescribed for fill wall systems for highway projects is allowable differential settlement. If substantial differential settlements are expected for a fill wall system, a relatively flexible wall system, i.e., a wall system that can tolerate differential movements without undergoing significant structural distress, should be considered. Representative tolerances for fill wall systems are given in table 3.

Advantages and disadvantages related to performance, constructability, and aesthetics of each fill wall system are also presented in table 3. Comparisons between systems are made where appropriate.

4.3.3 Selection Summary Chart for Cut Walls

The selection summary chart for cut walls (table 4) is presented and discussed in this section. The presentation and format of this table are similar to that for fill walls (table 3), but the selection issues related to performance are different. This is due primarily to the difference in the overall method of construction of cut walls (i.e., top-down). In section 4.4, table 4 is employed to illustrate the selection of a cut wall system for a specific project application.

The design life for cut wall systems is indicated in table 4. Most cut walls can be used for both temporary and permanent applications. The differences between temporary and permanent cut wall systems are that permanent systems are typically designed with greater corrosion protection measures and are constructed with permanent facing elements such as CIP or precast concrete panels. Micropile walls, however, are used primarily to stabilize active landslides, and are thus considered as permanent wall systems only.

The various selection factors for fill walls related to wall system cost and geometry are also applicable to cut walls. In table 4, ranges of values for cost-effective wall height, cost per square meter of wall face, and required ROW are provided. For cut walls without ground anchors, little or no ROW is required. For anchored walls and soil-nailed walls, significant ROW or permanent easements may be necessary so that adequate pullout resistances of the ground anchors or soil nails can be developed. For permanent applications, it may be necessary to purchase permanent easements for the ground anchors or the soil nails. Cut walls typically require specialized equipment and labor.

Costs can vary significantly for cut walls depending on the specific wall being constructed and the availability of experienced contractors and equipment in the project location. For cut walls, the unit cost of the wall increases as the height of the wall increases. For wall heights greater than approximately 5 meters, an anchored wall or a soil-nailed wall is necessary. Additional cost results from the material procurement, drilling, installation, corrosion protection, and testing of the anchors or soil nails. For all permanent wall systems except micropile walls, factors affecting costs include constructing an aesthetically pleasing wall finish, fabricating and installing special connections for the facing panels, and, if necessary, providing adequate long-term corrosion protection and constructing drainage systems. As such, the upper end of the cost range reported in table 4 is generally applicable to permanent cut wall systems.

In table 4, two key performance factors are summarized for cut wall systems. These issues are: (1) lateral movements; and (2) water tightness. Depending on the wall system, the lateral movements of cut walls depend in large measure on the bending stiffness of the vertical wall elements, the strength of the retained soil, the size and spacing of anchors or soil nails, and the workmanship involved in constructing the wall. Lateral wall movement provides an indication of likely ground surface settlements behind the wall, with the maximum lateral wall movement and the maximum ground surface settlement being approximately proportional. Watertightness of the wall is controlled by minimizing gaps in the wall system and decreasing the "permeability" of the wall. The importance of controlling lateral movements and/or flow of water in and around the wall is a function of the specific project constraints and requirements. For example, if a structure founded on shallow footings is located near the wall, large lateral movements and/or drawdown of the ground- water table may induce settlements that may cause architectural or structural damage. Conversely, if the ground-water table is located below the base of the wall and if lateral movements are not a concern, these two issues may be considered irrelevant to the selection process.

Advantages and disadvantages related to performance, construction, and environmental issues of each cut wall system are also presented in table 4.

4.4 WALL SYSTEM SELECTION EXAMPLES

4.4.1 General

In this section, the process of initial selection of fill and cut wall systems is illustrated using two examples. In each example, it is assumed that the need for an earth retaining system has been identified (Step 1, figure 45). An overview of the project application including a description of the function of the wall and the project location is provided for each example.

Wall system selection is illustrated in each example using the wall system selection flowchart (figure 45) and the information provided in the wall system selection summary tables (i.e., table 3 for fill walls or table 4 for cut walls). The commentary provided for each example explains the logic and decision-making involved in eliminating wall systems from consideration and in selecting one or several wall systems for the example project application.

It should be noted that these examples are intended to be instructive and have been developed for conditions that may exist for a given highway application. Therefore, general conclusions concerning wall system selection should not be drawn from the information presented in these examples.

Table 3. System selection chart for fill walls.

Wall Type	Perm.	Temp.	Cost Effective Height Range	Cost in \$ per m^2 of wall face[1]	Required ROW[2]	Differential Settlement Tolerance[3]	Advantages	Disadvantages
Concrete gravity wall	✓		1 - 3 m	270 - 370	0.5 - 0.7H[4]	1/500	· durable · requires smaller quantity of select backfill as compared to MSE walls · concrete can meet aesthetic requirements	· deep foundation support may be necessary · relatively long construction time
Concrete cantilever wall	✓		2 - 9 m	270 - 650	0.4 - 0.7H[4]	1/500	· durable · requires smaller quantity of select backfill as compared to MSE walls · concrete can meet aesthetic requirements	· deep foundation support may be necessary · relatively long construction time
Concrete counterforted wall	✓		9 - 18 m	270 - 650	0.4 - 0.7H[4]	1/500	· durable · requires smaller quantity of select backfill as compared to MSE walls · concrete can meet aesthetic requirements	· deep foundation support may be necessary · relatively long construction time
Concrete crib wall	✓		2 - 11 m	270 - 380	0.5 - 0.7H	1/300	· does not require skilled labor or specialized equipment · rapid construction	· difficult to make height adjustments in field
Metal bin wall	✓		2 - 11 m	270 - 380	0.5 - 0.7H	1/300	· does not require skilled labor or specialized equipment · rapid construction	· difficult to make height adjustments in field · subject to corrosion in aggressive environment
Gabion wall	✓		2 - 8 m	270 - 540	0.5 - 0.7H	1/50	· does not require skilled labor or specialized equipment	· need adequate source of stone · construction of wall requires significant labor
MSE wall (precast facing)	✓		3 - 20 m	240 - 380	0.7 - 1.0H	1/100	· does not require skilled labor or specialized equipment · flexibility in choice of facing	· requires use of select backfill · subject to corrosion in aggressive environment (metallic reinforcement)
MSE wall (modular block facing)	✓		2 - 7 m	175 - 275	0.7 - 1.0H	1/200	· does not require skilled labor or specialized equipment · flexibility in choice of facing · blocks are easily handled	· requires use of select backfill · subject to corrosion in aggressive environment (metallic reinforcement) · positive reinforcement connection to blocks is difficult to achieve
MSE wall (geotextile/geogrid/ welded wire facing)	✓	✓	2 - 15 m	165 - 380	0.7 - 1.0H	1/60	· does not require skilled labor or specialized equipment · flexibility in choice of facing	· facing may not be aesthetically pleasing · geosynthetic reinforcement is subject to degradation in some environments
Reinforced Soil Slopes (RSS)	✓	✓	3 - 30 m	80 - 260	0.5 - 1.0H	1/60	· does not require skilled labor or specialized equipment · flexibility in choice of facing · vegetation provides ultraviolet light protection to geosynthetic reinforcement	· facing may not be aesthetically pleasing · geosynthetic reinforcement is subject to degradation in some environments · vegetated soil face requires significant maintenance

Notes: (1) Total installed costs in 1995 U.S dollars.
(2) ROW requirements expressed as the distance (as a fraction of wall height, H) behind the wall face where fill placement is generally required for flat backfill conditions, except where noted.
(3) Ratio of the difference in vertical settlement between two points along the wall to the horizontal distance between the points.
(4) ROW requirement given is the typical wall base width as a fraction of wall height, H.

Table 4. System selection chart for cut walls.

Wall Type	Perm.	Temp.	Cost Effective Height Range	Cost in $ per m^2 of wall face(1)	Required ROW(5)	Lateral Movements	Water Tightness	Advantages	Disadvantages
Sheet-pile wall	✓	✓	up to 5 m	160 - 430	None	large	fair	· rapid construction · readily available	· difficult to construct in hard ground or through obstructions
Soldier pile/ lagging wall	✓	✓	up to 5 m	110 - 380	None	medium	poor	· rapid construction · soldier beams can be drilled or driven	· difficult to maintain vertical tolerances in hard ground · potential for ground loss at excavated face
Slurry (diaphragm) wall	✓	✓	6 - 24 m(2)	650 - 930	None(6)	small	good	· can be constructed in all soil types or weathered rock · watertight · wide range of wall stiffness	· requires specialty contractor · significant spoil for disposal · requires specialized equipment
Tangent pile wall	✓	✓	3 - 9 m 6 - 24 m(2)	430-810	None(6)	small	fair	· adaptable to irregular layout · can control wall stiffness	· difficult to maintain vertical tolerances in hard ground · requires specialized equipment · significant spoil for disposal
Secant pile wall	✓	✓	3 - 9 m 6 - 24 m(2)	430-810	None(6)	small	fair	· adaptable to irregular layout · can control wall stiffness	· requires specialized equipment · significant spoil for disposal
Soil mixed wall	✓	✓	6 - 24 m(2)	430 - 590	None(6)	small	fair	· adaptable to irregular layout	· requires specialized equipment · relatively small bending capacity
Anchored wall	✓	✓	5 - 20 m(3)	160 - 810	0.6 H + anchor bond length	small-medium	N/A	· can resist large horizontal pressures · adaptable to varying site conditions	· requires skilled labor and specialized equipment · anchors may require permanent easements
Soil-nailed wall	✓	✓	3 - 20 m	160 - 600	0.6 - 1.0H	small-medium	N/A	· rapid construction · adaptable to irregular wall alignment	· nails may require permanent easements · difficult to construct and design below water table
Micropile wall	✓		N/A	3,200-9,800(4)	Varies	N/A	N/A	· does not require excavation	· requires specialty contractor

Notes: (1) Total installed costs in 1995 U.S. dollars.
(2) Height range given is for wall with anchors.
(3) For soldier pile and lagging wall only.
(4) Cost per linear meter of wall.
(5) ROW requirements expressed as the distance (as a fraction of wall height, H) behind the wall face where wall anchorage components (i.e., ground anchors and soil nails) are installed.
(6) ROW required if wall includes anchors.

4.4.2 Fill Wall Selection Example

An existing highway embankment needs to be widened by 5 m to provide space for an additional traffic lane. A fill wall system is required because insufficient ROW is available to widen the embankment and maintain 2H:1V embankment side slopes. The overall geometry of this project example and soil stratigraphy are shown in figure 46. The selection of a permanent fill wall system is described below for this project example. The discussion presented for this example follows Steps 2 to 4 of the wall system selection flowchart (figure 45).

Step 2: Identify Site Constraints and Project Requirements

The following site constraints and project requirements exist for this example:

- the proposed wall height is 3.75 m;
- the available ROW extends 6 m from the edge of the existing highway shoulder;
- a minimum of 1 m clear space is required in front of the wall;
- a fiber optic cable, which cannot be relocated during wall construction, is located 1 m directly below the edge of the existing shoulder;
- vehicle traffic on the existing highway cannot be disrupted during construction;
- excavated material, if any, must be removed from the site;
- to minimize the possibility of damage to the cable and to provide worker safety, construction activities must occur beyond the edge of the existing shoulder;
- a traffic barrier must be constructed along the top of the wall; and
- the wall facing must have an exposed aggregate finish.

Based on the above factors, several fill wall systems can be eliminated from further consideration. The proposed wall height of 3.75 m is outside the cost-effective height range for concrete gravity walls and concrete counterfort walls. Gabion walls and wrap-around facing (i.e., geotextile, geogrid, and welded wire) walls and RSS are also inappropriate for this project example based on the wall facing requirement. Also, prefabricated modular concrete blocks are not available with an exposed aggregate finish. All remaining fill wall systems such as concrete cantilever walls; MSE walls with segmental, precast facing; bin walls; and crib walls can be constructed to meet the height, facing, and traffic barrier requirements.

Further evaluation of the remaining candidate wall systems requires information on subsurface conditions. A subsurface investigation is needed to evaluate the strength and compressibility of the wall foundation soils and retained soils as well as the ground-water conditions. The investigation should also include identification of potential sources of acceptable borrow material to be used as wall backfill. For this project example, several test borings were advanced to a depth of 8 m (approximately twice the wall height) below the ground surface along the alignment of the wall and in front of the wall. The following geotechnical information was obtained from the borings:

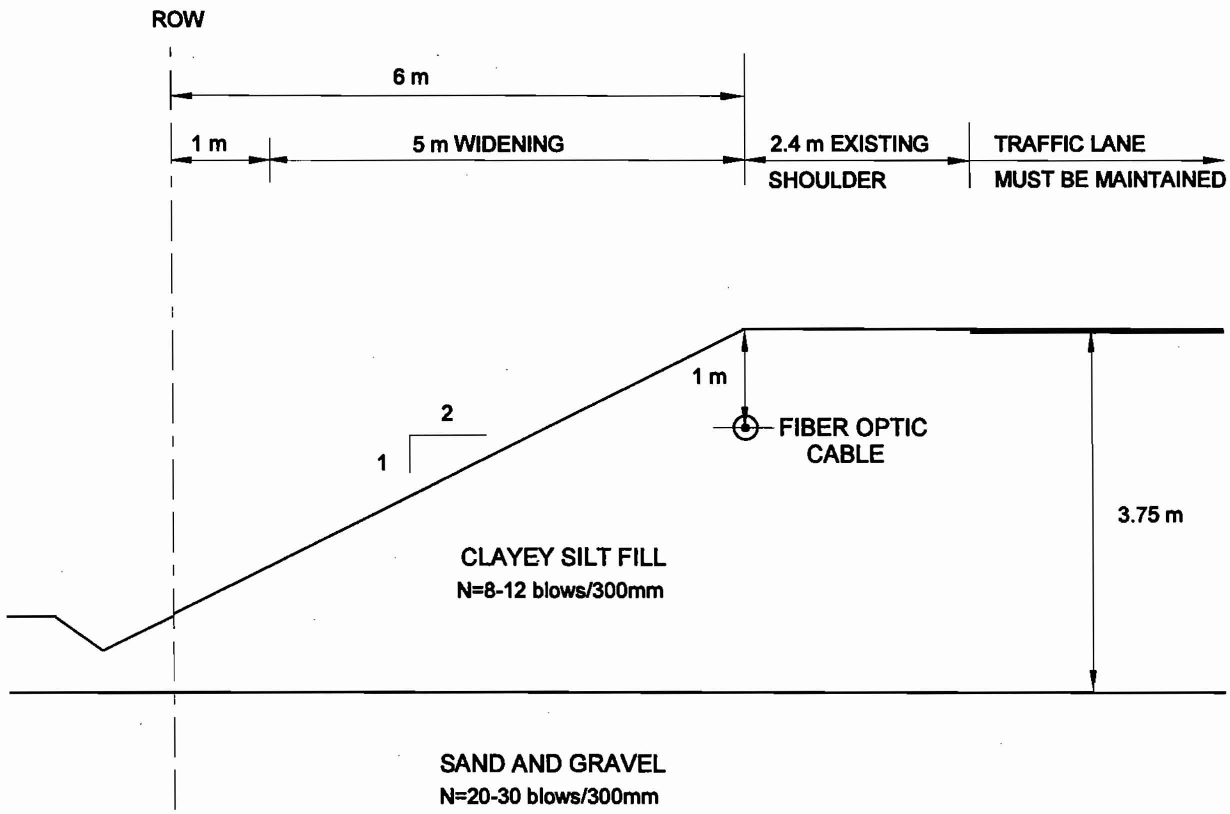


Figure 46. Geometry and site stratigraphy for fill wall example.

- The soil stratigraphy at this site consists of a 3.75-m thick layer of a clayey silt fill overlying sands and gravels. The sand and gravel layer extends to at least a depth of 8 m.

- In the upper fill layer, standard penetration test (SPT) blowcounts (N) range from 8-12 blows/300-mm and in the underlying sand and gravel layer, the SPT blowcounts range from 20-30 blows/300-mm. Based on the consistency of the clayey silt fill layer, the steepest safe excavation slope in the material is judged to be 1H:1V.

- Ground water was not encountered.

The sand and gravel layer is mined in a nearby quarry. This material is free-draining and appropriate for wall backfill for a permanent fill wall application.

Step 3: Evaluate Wall System Alternates

Based solely on the results obtained from the subsurface investigation, none of the remaining wall systems need be eliminated from consideration. Aside from cost, the selection of a fill wall system for this example is primarily influenced by the geometric constraints of the project. The necessary ROW for the candidate wall systems is shown in figure 47. These are based on minimum ROW requirements for these types of wall systems as reported in table 3. The feasibility of each of the fill wall systems is discussed below in relation to the five selection factors included as part of Step 3 of the selection flowchart.

- <u>Performance</u>
  The wall will be founded on the sand and gravel layer. It is not expected that excessive settlements will occur, nor, if a concrete cantilever wall is selected, will it be necessary to construct a deep foundation.

- <u>Construction</u>
  There are no constructability constraints associated with the construction of any wall system for this project example. Deep foundation support is not necessary for cantilever wall construction so large pile driving and/or drilling equipment is not required. All existing vegetation and topsoil should be stripped to minimize backfill settlement; this does not present any problems for the systems being considered. Specialized equipment and labor are not required for the construction of a MSE wall with segmental, precast facings, a crib wall, or a bin wall.

  As shown in figure 47, the steepest safe allowable excavation slope for the embankment soils is 1H:1V. This requirement necessitates the use of temporary excavation support for the construction of an MSE wall with segmental, precast facings, a bin wall, or a crib wall.

- <u>Aesthetics</u>
  All of the candidate wall systems can be constructed with an exposed aggregate wall finish.

- <u>Environmental</u>
  The sand and gravel to be used as wall backfill meets gradation requirements and minimum electrochemical criteria for MSE walls. Also, the ground-water table is located below the level of where any in-situ reinforcement would be constructed. This environment is suitable for both metallic and geosynthetic reinforcement.

  The construction of MSE walls with segmental, precast facings, bin walls, or crib walls requires excavation of the embankment materials. The costs associated with removing excavated material from the site should be considered.

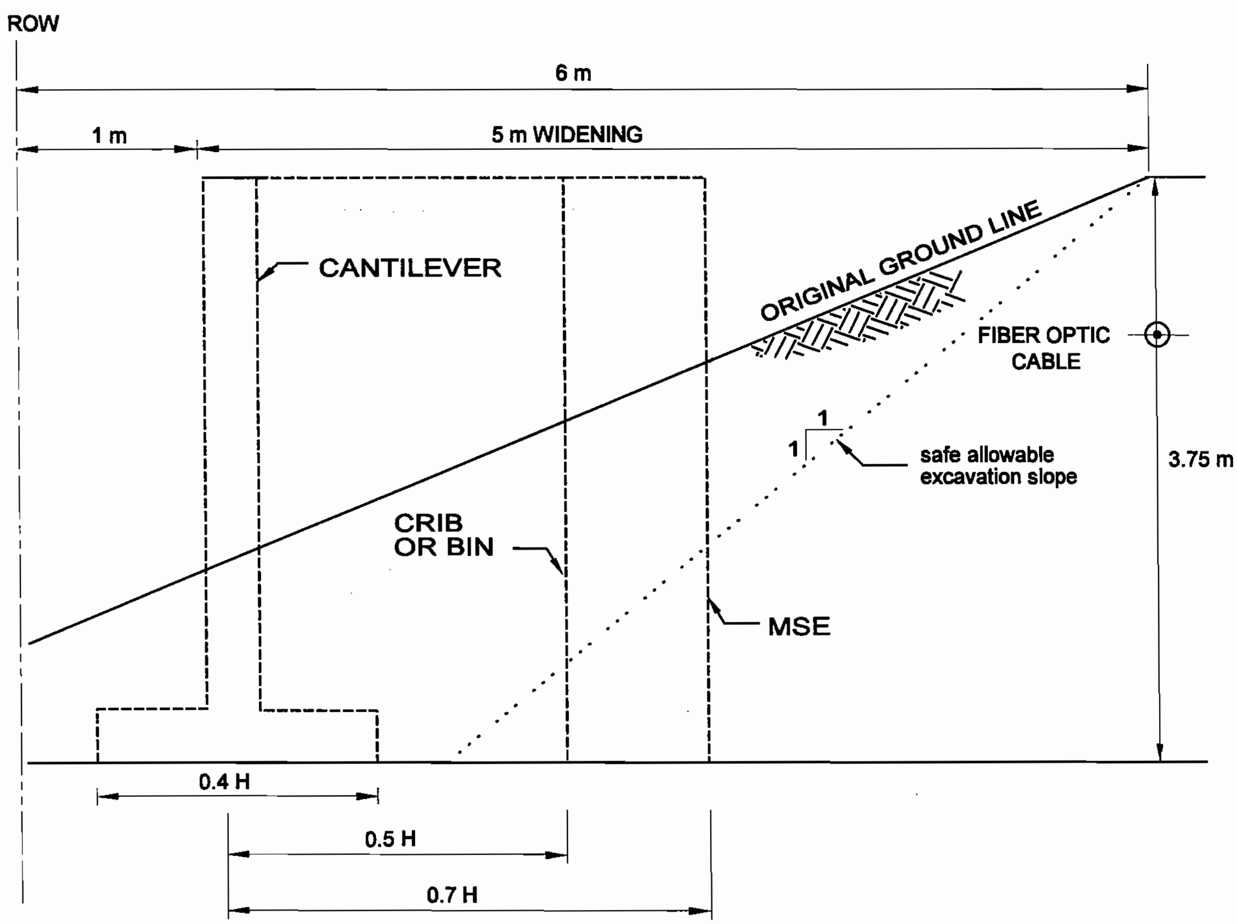


Figure 47. Geometry requirements for candidate wall systems.

- Geometry

  The ROW requirements, position of the fiber optic cable, and the maximum safe allowable excavation slope indicate that several wall systems will require temporary excavation support for construction. Cantilever walls, however, can be constructed within the available area without temporary excavation support.

Step 4: Select Wall Systems

The selection process has identified that concrete cantilever walls, MSE walls with segmental, precast facing, bin walls, or crib walls are well-suited to the project requirements. All of these systems are technically feasible and practical to construct for this project application. At this stage, a detailed cost estimate of each wall system should be prepared. A factor to be considered is whether the cost of a concrete cantilever wall is greater than the cost of other wall systems which require constructing temporary excavation support and removing excavated material from the site.

The width of the wall base assumed for the concrete cantilever wall (i.e., 0.4 H) is on the low end of the range of typical base width sizes for concrete cantilever walls. For walls with small base widths, it may be difficult to achieve an acceptable factor of safety against sliding. Typically, concrete cantilever walls may be designed with shear keys that penetrate the underlying foundation to provide additional sliding resistance. This should be considered for the cantilever wall described herein and all costs associated with constructing a shear key should be included in the cost estimate.

4.4.3 Cut Wall Selection Example

The construction of a depressed section of a highway requires an earth retaining system to support an excavation with a length of 500 m and a maximum height of 10 m. Several five story, masonry apartment buildings are located approximately 5 m behind the proposed wall location. The buildings are founded on shallow footings. The overall geometry and soil stratigraphy for this project example are shown in figure 48. The selection of a permanent, cut wall system for this project example is described below. The discussion presented for this example follows Steps 2 to 4 of the wall system selection flowchart (figure 45).

Step 2: Identify Site Constraints and Project Requirements

The following site constraints and project requirements exist for this example:

- the maximum excavation height is 10 m;
- the nearby apartment buildings could be damaged as a result of ground movements and ground-surface settlements and/or construction-induced vibrations;
- there is a town ordinance limiting construction noise; and
- the wall face must be aesthetically pleasing.

Based on the above factors, all non-gravity cantilevered walls can be eliminated from further consideration since the height of the excavation is 10 m. Without ground anchors, the cost effective height range for relatively flexible steel sheet-pile and soldier pile and lagging walls is only up to 5 m, and for large diameter, more heavily reinforced tangent and secant pile walls, the maximum height is 9 m. Either an anchored wall or a soil-nailed wall is needed to meet the wall height requirement for this project. Based on discussions with the property owner, it is determined that underground easements are available to allow installation of ground anchors or soil nails.

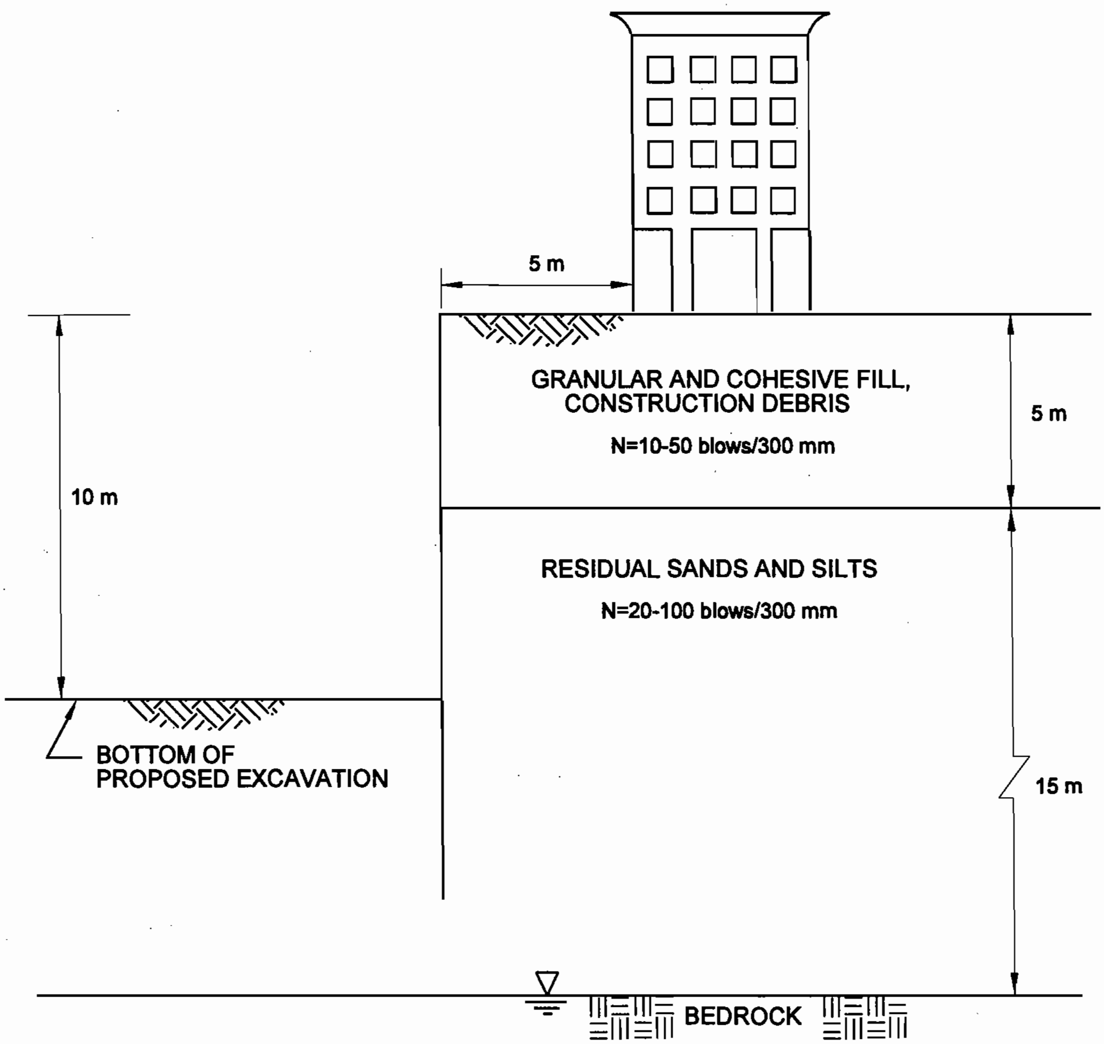


Figure 48. Geometry and site stratigraphy for cut wall example.

Micropile walls can also be eliminated from further consideration. These walls are typically used for slope stabilization and ground reinforcement, and are generally not cost-effective for the specific wall application described in this example.

Further evaluation of the remaining candidate wall systems requires information on subsurface conditions. It is necessary to evaluate the strength and stiffness of the in-situ soils as well as the ground-water conditions to adequately assess the influence of ground movements and ground surface settlements on the integrity of the apartment buildings. Information on subsurface conditions will also allow evaluation of wall system constructability. A subsurface exploration program was undertaken to address these issues. Several test borings were advanced to a depth of 20 m below the ground surface along the alignment of the wall and behind the proposed wall. The following geotechnical information was obtained from the borings:

- The soil stratigraphy at this site consists of a 5-m thick layer of granular and cohesive fill with construction debris overlying a 15-m thick layer of dense residual sands and silts. Bedrock was encountered at a depth of 20 m.

- In the upper fill layer, SPT blowcounts range from 10-50 blows/300-mm and in the underlying sand and silt layer, the SPT blowcounts range from 20-100 blows/300-mm.

- The ground-water table is located 20 m below the ground surface at the interface between the sand and silt layer and the bedrock.

Step 3: Evaluate Wall System Alternates

Based on the site constraints, project requirements, and the results of the subsurface exploration program, several additional wall systems can be eliminated from further consideration. The feasibility of each cut wall system is discussed below in relation to the five selection factors included as part of Step 3 of the selection flowchart.

- Geometry
  Other than the restriction imposed by the required excavation depth of 10 m, no other geometric constraints exist.

- Construction
  Given the high density of the sand and silt layer, it would be difficult to drive steel sheet-pile or soldier piles through this layer. Soldier piles could, however, be installed in predrilled holes if appropriate drilling procedures are used.

  Based on constructability, anchored walls with vertical wall elements installed in predrilled holes are technically feasible for this project example.

- Performance
  The masonry apartment buildings are susceptible to cosmetic or structural damage resulting from excessive ground movements and ground-surface settlements. Such damaging movements could be induced by lateral wall deformations. Although excessive ground movements and ground-surface settlements are not expected due to the presence of the dense silt and sand layer, the close proximity of the apartment buildings and the possible variability of the upper fill layer dictate that only wall systems that typically undergo relatively small lateral deformations should be considered for construction.

  For some wall systems, a stiff, impermeable wall may be necessary to prevent excessive ground movements. These systems include: (1) slurry (diaphragm) walls; (2) tangent pile walls; (3)

secant pile walls; and (4) steel-reinforced soil mixed walls. These wall systems are relatively expensive since their construction generally requires specialized equipment and construction materials, as well as a skilled specialty contractor. Therefore, unless excessive movements are anticipated for the other wall systems, these wall systems are not considered to be cost-effective for this project example.

The remaining feasible wall systems include: (1) an anchored soldier pile and lagging wall; and (2) a soil-nailed wall.

- Aesthetics

  For this project, it is necessary to construct an aesthetically pleasing wall. This requirement can be met for any of the cut wall systems by constructing a permanent facing over the wall face. For an anchored soldier pile and lagging wall, shear studs may be welded to the flanges of the soldier beams and a permanent concrete facing can be cast, or precast concrete panels can be connected to the wall using various connection devices. Cast-in-place concrete, steel reinforced shotcrete, and precast concrete panels are used to provide a permanent facing for soil-nailed walls. Various connection methods and devices are used in the construction of permanent facings for soil-nailed walls.

- Environmental

  Minimal noise and vibration is associated with the construction of anchored, predrilled, soldier pile and lagging walls or soil-nailed walls.

Step 4: Select Wall Systems

The selection process has identified that anchored soldier pile and lagging walls and soil-nailed walls are well-suited to the project requirements. Both systems are technically feasible and practical to construct for this project application. Soil-nailed walls, however, typically undergo more lateral deformation than anchored soldier pile and lagging walls. Therefore, a more detailed assessment of the tolerable lateral movements of the wall system should be performed to ascertain the applicability of a soil-nailed wall for this project example.

CHAPTER 5

DESIGN OVERVIEW

5.1 INTRODUCTION

The purpose of this chapter is to present an overview of the design of earth retaining systems. It is not the intent of this chapter, nor is sufficient information presented, to enable the user to carry out detailed analysis and design for any of the earth retaining systems discussed. Instead, a discussion of major design topics for fill and cut walls is presented herein. The reader is directed to appropriate references for detailed design and analysis procedures.

A general design methodology that is valid for both fill and cut walls is outlined in table 5. Step (1) involves establishing overall geometric requirements for the wall application and project requirements and constraints. This involves developing the wall profile, locating wall appurtenances such as traffic

Table 5. Typical design steps for earth retaining systems.

(1)	Establish project requirements including wall geometry, external loadings, performance criteria, and construction constraints.
(2)	Evaluate site subsurface conditions and properties of in-situ soil and rock.
(3)	Select wall system.
(4)	Select wall construction materials. Evaluate design properties.
(5)	Establish design factors of safety.
(6)	Determine preliminary wall dimensions.
(7)	Evaluate lateral earth pressures on back of wall.
(8)	Check external stability and revise dimensions if necessary.
(9)	Check internal stability and revise dimensions if necessary.
(10)	Estimate vertical and differential settlement and lateral wall movements. Revise dimensions if necessary.
(11)	Design auxiliary components such as drainage systems and facing systems.
(12)	Identify contracting approach and prepare appropriate contract documents.

barriers, utilities, and drainage systems, establishing right-of-way (ROW) limitations, and construction sequencing requirements. Project requirements and constraints may significantly affect design, construction, and cost of the wall system and should therefore be identified during the early stages of project implementation. Step (2) includes evaluating geotechnical properties necessary for wall design, as discussed in this chapter; Step (3) involves wall system selection following the methodology described in chapter 4. Steps (4) through (11) address specific geotechnical and structural design requirements, several of which are briefly described in this chapter. Wall system contracting, Step (12), is discussed in chapter 6.

The organization of the remainder of this chapter is described below.

- Geotechnical investigation is discussed in section 5.2. This section includes information on developing a subsurface profile and identifying ground-water levels as part of subsurface exploration activities. Descriptions of in-situ and laboratory testing techniques that may be used to evaluate design parameters for backfill soils, retained soils, and foundation material (i.e., soil or rock) are also discussed in this section.

- Earth pressures are discussed in section 5.3. This section includes descriptions of theoretical and semi-empirical lateral earth pressure diagrams for use in design of fill and cut walls. Earth pressures resulting from loads applied at the ground surface are also described in this section.

- Design concepts related to fill and cut walls are described in section 5.4. Topics related to external stability, internal stability, and structural design are presented in this section.

- Other design elements frequently included in the design of fill and cut walls are discussed in section 5.5. These include: (1) wall embedment; (2) wall drainage systems; (3) seismic wall design; and (4) wall system appurtenances.

- A list of relevant design reference manuals and publications is provided in section 5.6. The listed references contain detailed analysis techniques and design methods for the wall systems described in this document.

5.2 GEOTECHNICAL INVESTIGATION

5.2.1 Introduction

The engineering properties and behavior of backfill, retained soil, and foundation material must be evaluated because these materials are the major sources of both loading and support for any earth retaining system. The evaluation of retained soil and foundation materials is typically made through a geotechnical subsurface investigation and borrow source evaluation and a laboratory or in-situ testing program. The evaluation of backfill material is typically made through a laboratory testing program. These evaluations are discussed in the remainder of this section.

5.2.2 Subsurface Investigation and Testing Program

5.2.2.1 Background

A subsurface investigation generally includes field reconnaissance, subsurface exploration, and in-situ or laboratory soil testing. In addition to evaluating the engineering behavior of retained soil and foundation material, the investigation should be designed to define:

- ground-surface topography;
- soil and rock stratigraphy;
- ground-water conditions;
- potential backfill borrow sources; and
- local conditions requiring special consideration.

The extent of the subsurface investigation should be consistent with the project scope (i.e., location, size, risk, and budget), the project objectives (i.e., purpose of the wall system), and the project constraints (i.e., geometry, constructability, performance, aesthetics, and environmental impact). Typical elements of a subsurface investigation are described in the following sections.

5.2.2.2 Field Reconnaissance

Field reconnaissance typically involves visual inspection of the site and examination of available documents pertaining to site conditions. Information collected during field reconnaissance should include the following:

- surface topography;
- site access conditions;
- surface drainage patterns;
- surface geologic patterns including rock outcrops, landforms, and existing excavations;
- existing below-grade utilities and substructures;
- available right-of-way (ROW); and
- areas of potential instability such as deep deposits of organic soils, slide debris, and areas with a high ground-water table.

5.2.2.3 Subsurface Investigation and In-situ Soil Testing

Subsurface investigation activities typically involve soil borings, rock coring, and/or test pits or trenches. Information on the subsurface soil stratigraphy and ground-water conditions are typically obtained from subsurface investigation activities. Subsurface investigation may also involve in-situ soil or rock testing, i.e., testing of material in its natural position below ground, and obtaining samples for laboratory testing. Specific details involved in developing a subsurface investigation program (i.e., spacing and depths of soil borings, sampling procedures for soils, spacing and depths of rock cores, location of test pits/trenches, etc.) are discussed in other documents (e.g., AASHTO, 1988).

Soil Stratigraphy

The soil stratigraphy at the project site, including the thickness and elevation of various layers, should be evaluated through implementation of a project-specific subsurface investigation. Problematic soils and rock should also be identified during the subsurface investigation as they may significantly affect the design and construction of a wall system. Examples include:

- cohesionless sands and silts which tend to ravel (i.e., cave-in) and which may be susceptible to seismically-induced liquefaction;
- weak soil or rock layers where the potential for sliding instabilities exist;
- highly compressible materials such as soft clays and organic soils;
- collapsible soils in arid regions; and
- obstructions, boulders, and cemented layers.

For example, if obstructions, hard soils, or bouldery soils are encountered during the subsurface investigation, it may be necessary to use heavier equipment for slurry (diaphragm) wall construction, whereas if running soils (i.e., cohesionless sands and silts) are encountered, modifications of the slurry mix and/or shortening of the wall panel lengths should be considered to minimize the potential for trench cave-ins.

Borings should be advanced at regular intervals along, behind, and in front of the wall alignment. For anchored walls, borings should be advanced behind the proposed wall line within the anchor bond zone, and for soil-nailed walls, within the potential failure zone. For MSE walls and RSS, borings should be advanced just behind the reinforced backfill zone. Boring depths should be controlled by the general subsurface conditions, but should penetrate to a depth of at least twice the height of the wall system. Borings should be advanced deeper if there is a potential for soft, weak, collapsible, or liquefiable soils at depth. Soil samples should be obtained at regular intervals and at changes in underlying soil strata for visual identification and laboratory testing. Methods of sampling include Standard Penetration Testing (SPT) (ASTM D 1586) and pushed thin-wall (Shelby) tube sampling (ASTM D 1587).

Ground Water

Ground-water table and any perched ground-water zones must be evaluated as part of a subsurface investigation program as it has a significant effect on the design and construction of an earth retaining system. The presence of ground water affects lateral pressures applied to the wall facing, drainage system design, and construction procedures. At a minimum, the following items need to be considered for wall systems that will be constructed within or near the water table:

- corrosion potential of metallic components based on the acidity/alkalinity of the ground water;
- reduction in interface frictional resistance between structural components (e.g.,anchors, micropiles, soil nails, embedded vertical wall elements, and reinforcing elements) and soil;
- lateral pressures applied to the wall facing;
- necessity for excavation dewatering and specialized underwater drilling and grouting procedures; and
- liquefaction potential of loose, cohesionless soils.

Ground-water level information is often obtained by observation of the depth to which water accumulates in an open borehole at the time of exploration. It is important, however, to allow sufficient time to pass after borehole excavation so that water levels can reach equilibrium. More accurate measurements of water levels in the subsurface can be made using piezometers or observation wells, and by obtaining water level measurements over a duration of time to obtain an indication of potential water level fluctuations.

In-situ Soil Testing

Various in-situ testing techniques can be used to estimate specific soil and rock properties such as shear strength and in-situ state of stress. In-situ testing offers several advantages relative to laboratory testing of samples recovered from the field, including low cost, ability to test large volumes of material, and ability to test material in its natural state. The following testing procedures are widely used in the United States: (1) standard penetration test (SPT) (ASTM D 1586); (2) cone penetration test (CPT) (ASTM D 3441) (FHWA-SA-91-043, 1992); (3) vane shear test (ASTM D 2573); (4) pressuremeter test (ASTM D 4719) (FHWA-IP-89-008, 1989); and (5) flat plate dilatometer test (FHWA-SA-91-044, 1992). These tests are described below.

- *SPT*: This test is suitable for all soil types except gravels. This test can be used to estimate the effective stress friction angle and relative density of granular soils and the undrained strength of cohesive soils using correlations with SPT blow counts. Liquefaction potential has been correlated with SPT blowcounts. A disturbed soil sample is obtained during testing.

- *CPT*: This test is suitable for sands, silts, and clays. This test can be used to estimate the effective stress friction angle of granular soils and undrained shear strength of cohesive soils. Data obtained with this test can also be used to develop a detailed subsurface soil profile. Liquefaction potential has also been correlated to measured cone resistances. In-situ pore pressure can be measured with CPT devices equipped with pressure cells (i.e., piezocones).

- *Vane Shear*: This test is suitable for cohesive soils. This test is used to measure the peak and residual (remolded) undrained shear strength of these soils.

- *Pressuremeter*: This test is suitable for all soil types, except gravels. This test can be used to estimate horizontal soil modulus and the in-situ lateral state of stress. This test can also be used to evaluate the effective stress friction angle in granular soils and undrained shear strength in cohesive soils.

- *Flat Plate Dilatometer*: This test is suitable for soils that are finer than gravelly sands. This test can be used to evaluate the effective stress friction angle in granular soils and undrained shear strength in cohesive soils. This test can also be used to estimate the in-situ lateral state of stress. Several other soil properties, including liquefaction potential have also been correlated to test results.

Rock conditions should be evaluated for wall systems which are to be founded on rock or for systems which derive lateral resistance through anchorage in rock. If rock conditions are of interest, rock cores can be recovered and logged. A description of rock type, mineral fabric, foliation, degree of weathering, and discontinuities is generally obtained. An estimate of intact rock strength can be evaluated using percentage of core recovery and rock quality designation (RQD). The orientations (strikes and dips) of discontinuities (including both bedding planes and principal fracture sets) should be included in the rock description so that the potential for sliding instability resulting from the expected wall loads can be evaluated.

5.2.3 Laboratory Soil Testing

Laboratory testing of soil samples recovered during subsurface exploration is often performed to evaluate specific soil properties necessary for the design of an earth retaining system. In this section, laboratory tests typically performed to evaluate engineering, mechanical, and chemical properties of backfill, retained soil, and foundation materials are presented. This section also includes discussion of the applicability of the tests for specific wall types and conditions. Appropriate ASTM and AASHTO specifications are provided for the laboratory tests presented.

Soil Classification and Index Properties

All soil samples taken from borings should be visually identified in the laboratory and classified according to the Unified Soil Classification System (USCS). Index soil properties used in the analysis and design of earth retaining systems include unit weight, moisture content, gradation, and Atterberg limits. Unit weight of foundation material, backfill soil, and retained soil are used in evaluating earth pressures, and in evaluating the external and internal stability of the considered wall system. Moisture content (ASTM D 2216) information and Atterberg limits (ASTM D 4318; AASHTO T89, T90) may be used with existing correlations to estimate compressibility and shear strength of in-situ soils. Also, these data are used as an index to evaluate the creep potential of clay soils; anchors and soil nails are not appropriate for use in soils with high creep potential. The results of soil grain size distribution testing (ASTM D 422; AASHTO T88) can be used as an index to evaluate permeability and compaction characteristics of soil. Soil gradation information is also used to develop appropriate drilling and grouting procedures for anchored, micropile, and soil-nailed walls.

Shear Strength

Unconfined compression (ASTM D 2166; AASHTO T208), direct shear (ASTM D 3080; AASHTO T236), or triaxial compression (ASTM D 4767; AASHTO T234) testing is typically performed to evaluate soil shear strength. Shear strength parameters are used in the design of all wall systems for evaluation of: (1) foundation bearing capacity; (2) global stability of the wall system; (3) lateral earth pressures; and (4) interface shear resistance between structural components and the surrounding soil. For permanent wall applications involving cohesive soils, both undrained (end of construction) and drained (long term) strength parameters should be obtained, and the design of the wall system should consider both conditions. Total stress and effective stress strength parameters of cohesive soils are typically evaluated from the results of undrained triaxial tests with pore pressure measurements. For wall applications involving cohesionless soils, direct shear or triaxial compression testing can be used to evaluate drained shear strength. Typically, however, drained shear strength of cohesionless soils is evaluated based on correlations with in-situ test results (e.g., SPT and CPT testing), as it is difficult to obtain undisturbed samples of these materials.

Consolidation Characteristics

Settlement analyses should be performed for walls founded on compressible soils. As indicated in Chapter 2 of this document, excessive total and/or differential settlement may be detrimental to the long-term performance of many types of wall system. For instance, large differential settlements between the wall face and the backfill soil may induce significant distress in facing/reinforcement connections. Differential settlements along the wall alignment may affect the overall wall appearance (aesthetics) and performance of the wall facing for both fill and cut wall systems. The results of index tests including moisture content (ASTM D 2216) and Atterberg limits (ASTM D 4318; AASHTO T89, T90) can be used for initial evaluation of settlement parameters. The results of one-dimensional consolidation (ASTM D 2435; AASHTO T216) tests are often used to evaluate the parameters necessary for settlement analysis.

Drainage and Compaction Characteristics

Backfill soils for fill walls are typically granular, non-plastic, and free-draining to ensure adequate performance of the wall system throughout the design life. Grain size distribution testing (ASTM D 422; AASHTO T88) and Atterberg limits testing (ASTM D 4318) are used to evaluate soil gradation and plasticity. The effective particle size (D_{10}), which is obtained from grain size distribution testing, can be used to estimate the permeability of uniform granular soils.

Backfill and foundation soils are compacted for fill wall construction to increase soil shear strength and stiffness and decrease compressibility. Compaction tests can be performed in the laboratory using either standard (ASTM D 698; AASHTO T99) or modified Proctor (ASTM D 1577; AASHTO T189) compaction effort to evaluate the moisture-density relationship for the backfill and foundation soils. This relationship can then be used to establish minimum criteria for the field-compaction of each lift of the backfill soils and for the preparation of the foundation soils.

Electrochemical Criteria

For wall systems that employ metallic or geosynthetic elements embedded in soil, the aggressiveness of the soil must be considered. For metallic elements such as steel reinforcement in MSE walls and anchors and soil nails, corrosion potential is of primary concern and is evaluated based on results of tests to measure the following soil properties: (1) pH (AASHTO T289); (2) electrical resistivity (AASHTO T288); (3) sulfate content (AASHTO T290); and (4) chloride content (AASHTO T291). Although geosynthetic reinforcement typically has high durability in most soil environments, polymer degradation can occur in some instances. Resistance to chemical attack may vary widely with polymer type. Degradation potential is evaluated based on the results of soil property tests that are appropriate for the polymer type being considered for use. These tests may include pH, calcium content, and iron content. More detailed information on the corrosion and durability of metallic and geosynthetic materials can be found elsewhere (FHWA-SA-96-072, 1996; FHWA-DP-68-1R, 1988).

5.3 EARTH PRESSURES

5.3.1 General

A wall system is designed to resist lateral earth pressures and water pressures that develop behind the wall. Earth pressures develop primarily as a result of loads induced by the weight of the backfill and retained soil, earthquake ground motions, and various surcharge loads. For purposes of earth retaining system design, three different lateral earth pressures are usually considered: (1) at-rest earth pressure; (2) active earth pressure; and (3) passive earth pressure.

- At-rest earth pressure is defined as the lateral pressure that exists in level ground for a condition of no lateral deformation.
- Active earth pressure is developed as the wall moves away from the backfill and the retained soil. This movement results in a decrease in lateral pressure relative to the at-rest condition. A relatively small amount of lateral movement is necessary to reach the active condition.
- Passive earth pressure is developed as the wall moves towards the backfill and the retained soil. This movement results in an increase in lateral pressure relative to the at-rest condition. The movements required to reach the passive condition are approximately ten times greater than those required to develop active earth pressure.

Each of these earth pressure conditions can be expressed by an equation with the general form:

$$\sigma_h = K\sigma_v \qquad (1)$$

where σ_h is the lateral earth pressure at a given depth behind the wall, σ_v is the vertical pressure at the same depth, and K is an earth pressure coefficient that can relate to at-rest earth pressure (K_o), active earth pressure (K_a), or passive earth pressure (K_p). Standard SI units are: σ_h (kPa), σ_v (kPa), and K (dimensionless).

The magnitude of K_p, K_o, and K_a vary according to the following relationship: $K_p > K_o > K_a$. The magnitude of the at-rest earth pressure coefficient is primarily a function of soil shear strength and degree of overconsolidation. The magnitude of the active and passive earth pressure coefficients are functions of the soil shear strength, the backfill geometry (i.e., horizontal backfill surface or sloped), the orientation of the surface where the wall contacts the backfill or retained soil (i.e., vertical or battered), and the friction that develops on this surface. The relationship between these earth pressure coefficients and their associated lateral movements are illustrated in figure 49.

5.3.2 Earth Pressure Diagrams

5.3.2.1 Introduction

Earth pressure diagrams serve to illustrate the overall loading on a wall system resulting from lateral earth pressures. The overall loading is illustrated in a cross-sectional view taken perpendicular to the

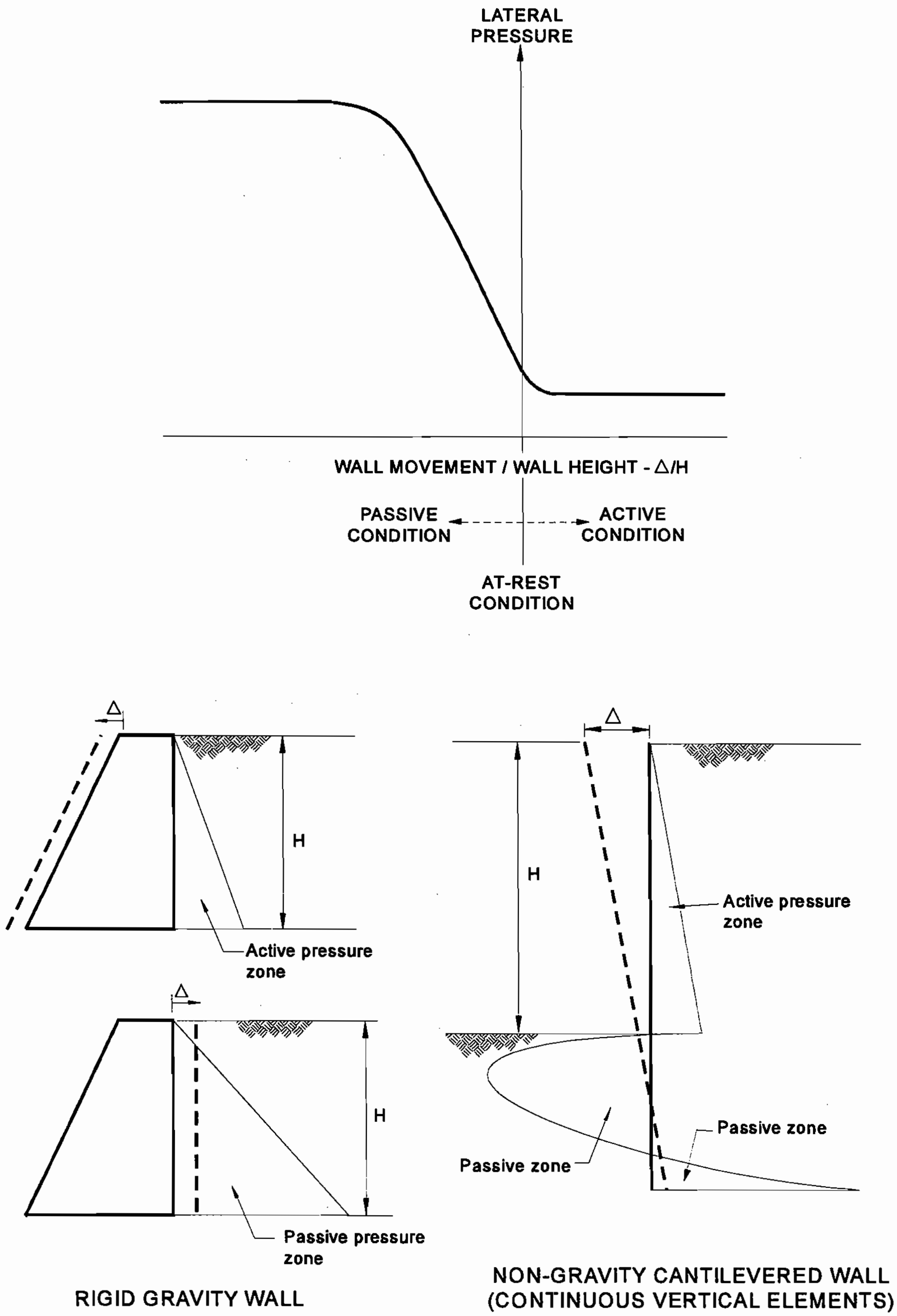


Figure 49. Magnitudes and patterns of movement to develop lateral earth pressures.

wall alignment. These diagrams are used during wall design to determine the total, or resultant, earth pressure forces acting on the wall system. Different earth pressure diagrams are used to design different wall systems because earth pressures vary with many factors, including shear strength and stiffness of the backfill or retained soil, stiffness and geometry of the wall, wall construction procedures and workmanship, movements of the wall, and other factors. In this section, theoretical and semi-empirical earth pressure diagrams used for external and internal stability analyses are introduced and issues related to the use of a particular type of earth pressure diagram for a wall design are discussed.

5.3.2.2 Theoretical Earth Pressure Diagrams

Values of the earth pressure coefficients, K_a and K_p, can be calculated using soil mechanics theories. The two most commonly used theories are: (1) Rankine theory; and (2) Coulomb theory. The primary difference between the two theories, for the common case of a horizontal backfill and a vertical surface of contact between the wall and the backfill or retained soil (the wall/soil interface), is that the Rankine theory assumes that no friction develops on the wall/soil interface, while the Coulomb theory allows for the development of friction at this interface. For the case of zero wall friction and horizontal backfill, the Coulomb and Rankine analyses are equivalent.

In many earth retaining wall applications, the backfill or retained soil settles relative to the wall and induces downward friction on the wall at the wall/soil interface. This downward friction tends to stabilize the wall. Therefore, for active earth pressure conditions the Rankine theory, which neglects such friction, is generally conservative with respect to the Coulomb theory, which accounts for such friction.

The Rankine and Coulomb theories are used for the design of all types of fill walls and for nongravity cantilevered walls, particularly for external stability evaluations. The Rankine theory produces a simple formula for K_a for the case of a wall with a vertical wall/soil interface and cohesionless, horizontal backfill or retained soil. In design practice, the Rankine formula is often used for this case because of its simplicity, despite the fact that wall/soil interface friction is neglected. The Coulomb theory is typically used for walls with inclined backfills and/or irregular surcharge loads and for horizontal-backfill walls where wall/soil interface friction is to be included. Active earth pressure resultant forces based on the Rankine and Coulomb theories are illustrated in figure 50. In figure 50, H is the height of the wall, γ' is the effective soil unit weight, and K_a is the active earth pressure coefficient. Standard SI units are: H (m); γ' (kN/m^3); and K_a (dimensionless).

A general equation for K_a and K_p, which is applicable for cases with a sloping backfill, wall/soil interface friction, and a sloping wall face, can be written as:

$$K_a = \frac{\cos^2(\phi-\theta)}{\cos^2(\theta)\cos(\theta+\delta)\left[1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi-\beta)}{\cos(\theta+\delta)\cos(\theta-\beta)}}\right]^2} \quad (2)$$

$$K_p = \frac{\cos^2(\theta+\phi)}{\cos^2(\theta)\cos(\theta-\delta)\left[1-\sqrt{\frac{\sin(\phi+\delta)\sin(\phi+\beta)}{\cos(\theta-\delta)\cos(\theta-\beta)}}\right]^2} \quad (3)$$

where ϕ is the effective stress friction angle, θ is the angle of wall inclination ($\theta=0°$ for vertical wall face), δ is the wall/soil interface friction angle, and β is the angle of backfill inclination ($\beta=0°$ for horizontal backfill surface). Standard SI units are: ϕ (degrees); θ (degrees); δ (degrees); and β (degrees). It should be noted that passive pressures calculated according to Coulomb theory may be significantly larger than that which can actually be mobilized in typical wall applications, especially for cases in which the wall/soil interface friction angle exceeds approximately one-third of the effective stress friction angle (NAVFAC, 1986).

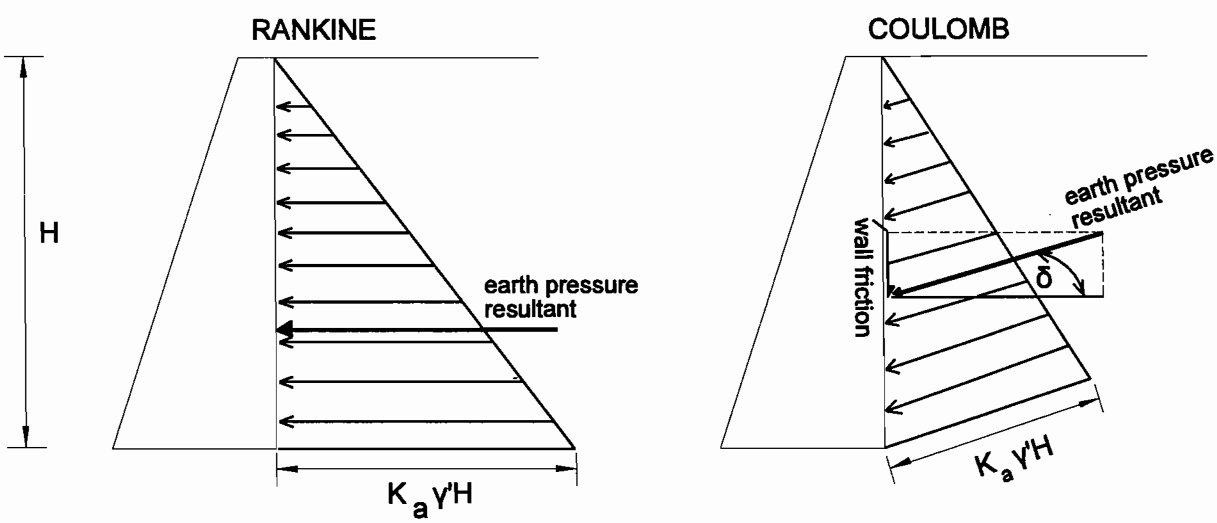


Figure 50. Active earth pressure distributions based on Rankine and Coulomb theories.

5.3.2.3 Semi-Empirical Earth Pressure Diagrams

Earth pressures used for the design of certain earth retaining systems are different from those computed based on theoretical Rankine or Coulomb analyses. The theoretical approaches do not consider the influence of wall system stiffness, the actual construction sequence of the wall system, and the magnitude and pattern of wall and ground movements. These factors are often considered semi-empirically by incorporating both theoretical considerations and information based on the performance of previously constructed wall systems into the design earth pressures. The design of anchored walls is generally performed using such semi-empirical earth pressure diagrams, as discussed in section 5.4.3 of this document.

Semi-empirical earth pressure diagrams are typically employed in internal stability evaluations of wall systems. For example, the maximum tension in each level of reinforcement for a MSE wall is assumed to be related to the vertical overburden pressure according to Eq. (1). The value for K used for this analysis varies depending on reinforcement type and is based on past performance data and experimental results (figure 51).

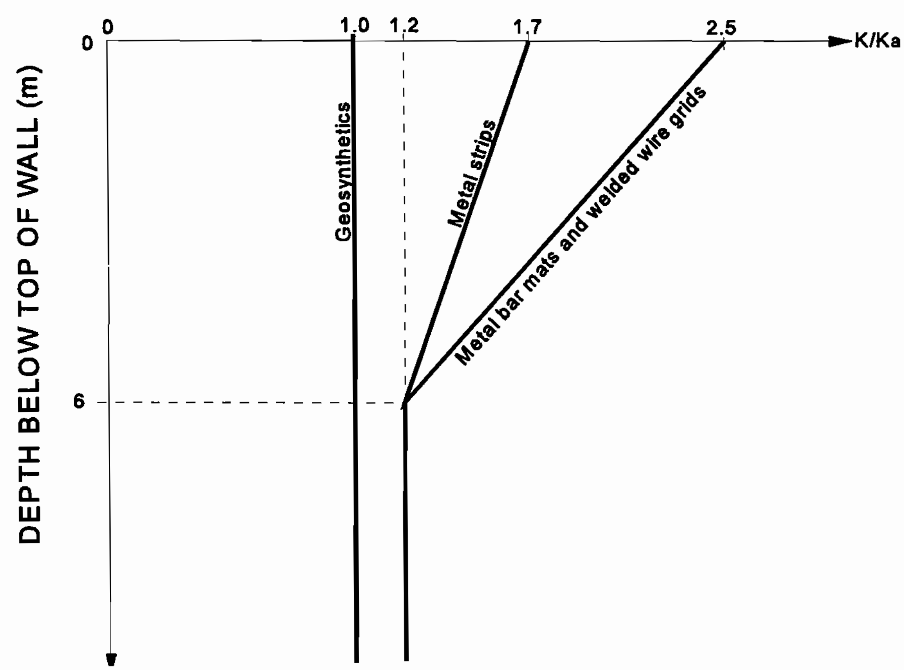


Figure 51. Variation of stress ratio with depth for MSE wall (modified after FHWA-SA-96-071, 1996).

The structural design of prefabricated modular gravity walls includes the evaluation of the lateral pressures which develop inside the modules. The calculated maximum pressure used for design of the wall members is based on bin pressure theory.

5.3.3 Earth Pressures due to Surface Loads

Additional earth pressures resulting from loads applied at the ground surface must also be included in the design of an earth retaining system. These earth pressures are generated by surface surcharge loads, point loads, line loads, and strip loads.

5.3.3.1 Surcharge Loads

Surcharge loads are vertical loads applied at the ground surface which are assumed to result in a uniform increase in lateral stress over the entire height of the wall. The increase in lateral stress for uniform surcharge loading can be written as:

$$\Delta\sigma_h = Kq_s \tag{4}$$

where $\Delta\sigma_h$ is the increase in lateral earth pressure due to the vertical surcharge load, K is an appropriate earth pressure coefficient, and q_s is the vertical surcharge load applied at the ground surface. Standard SI units are: $\Delta\sigma_h$ (kPa), K (dimensionless), and q_s (kPa). Examples of surcharge loads for highway wall system applications include: (1) dead load surcharges such as that resulting from the weight of a bridge approach slab or concrete pavement; (2) live load surcharges such as that due to traffic loadings; and (3) surcharges due to equipment or material storage during construction of the wall system. When traffic is expected to come to within a distance equivalent to one-half the wall height, the wall should be designed for a live load surcharge pressure of approximately 12 kPa. For design, it is common to assume a surcharge load of approximately 15 kPa to account for the effects of storage of construction materials and equipment. For situations in which heavy equipment must operate relatively close to the wall alignment, larger loadings may need to be considered.

5.3.3.2 Point Loads, Line Loads, and Strip Loads

Point loads, line loads, and strip loads are vertical surface loadings which are applied over limited areas as compared to surcharge loads. As a result, the increase in lateral earth pressure used for wall system design is not constant with depth as it is for uniform surcharge loadings. These loadings are typically calculated using equations based on elasticity theory for lateral stress distribution with depth (NAVFAC, 1986).

5.4 EARTH RETAINING SYSTEM DESIGN

5.4.1 Introduction

The purpose of this section is to present and discuss several design concepts relevant to fill and cut wall systems. A list of design reference documents that contain detailed descriptions of analysis techniques and step-by-step design procedures is provided in section 5.6. Topics discussed herein for fill and cut walls are listed below.

- Fill walls
  - external stability
  - backfill soil
  - wall foundations
  - internal stability and structural design

- Cut walls
  - earth pressure diagrams
  - corrosion protection of anchors and soil nails
  - internal stability and structural design

5.4.2 Fill Walls

5.4.2.1 External Stability

External stability analyses are used in design to evaluate the ability of the wall to resist lateral pressures applied by surcharges and the backfill and retained soil. The possible modes of external instability that are generally considered are illustrated in figure 52. Although figure 52 shows a cantilever wall, these modes of external instability are typically considered for all types of fill walls. Figure 53 shows the external forces that act on a typical wall system. A wall must be proportioned to ensure an adequate factor of safety (FS) against failure as described below.

Sliding

Sliding may occur when the lateral pressure on the wall exceeds the available lateral resistance along the base of the wall. The lateral resistance may have several components including frictional resistance and adhesion that can be mobilized between the base of the wall and the underlying wall foundation soil or rock and passive resistance from the soil in front of the wall or adjacent to any foundation keyways. Passive resistance from soil in front of the wall is

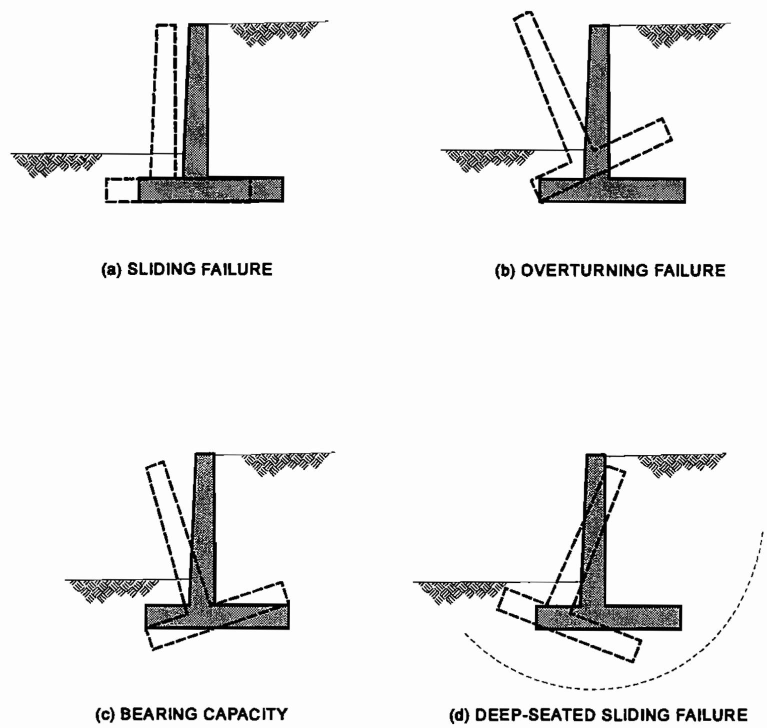


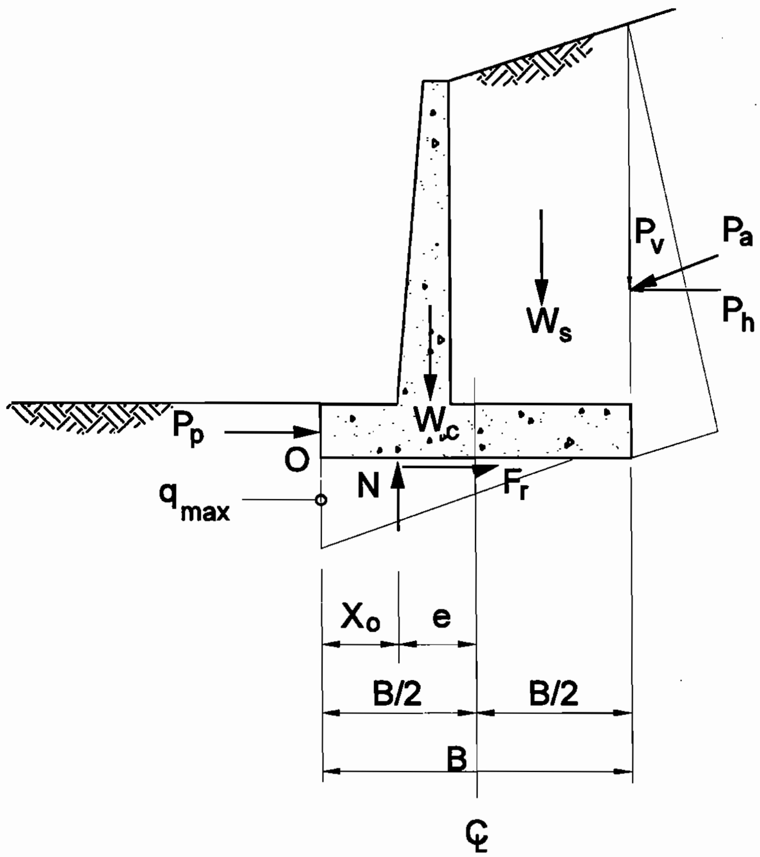
Figure 52. Modes of external stability for a fill wall (modified after NCHRP, 1991).

typically neglected for sliding stability calculations. For the case shown in figure 53, the factor of safety, FS, against sliding would be given as:

$$FS = \frac{F_r}{P_h} = \frac{N \tan\delta_B + C_B B}{P_h} \tag{5}$$

where N is the resultant vertical load, δ_B is the interface friction angle between the wall base and the foundation, C_B is the adhesion between the wall base and the foundation, B is the wall base width, and P_h is the horizontal earth pressure resultant. Standard SI units are: N (kN/m); δ_B (degrees); C_B (kPa); B (m); and P_h (kN/m). The minimum factor of safety against sliding is typically taken as 1.5 (AASHTO, 1994).

If an adequate factor of safety against sliding cannot be achieved, design modifications should be considered. Modifications may include: (1) increasing the width of the wall base; (2) using an inclined wall base or battering the wall to decrease the horizontal load; (3) constructing a shear key; and (4) embedding the wall foundation or slope base to a depth for which adequate lateral resistance can be mobilized. Other types of modifications include lengthening the reinforcement for MSE walls and RSS, using denser stone for gabion walls, and constructing a berm at the toe of a reinforced soil slope to act as a buttress.



NOTATIONS:

P_p = passive earth pressure resultant (kN/m)
P_a = active earth pressure resultant (kN/m)
W_s = weight of soil above heel (kN/m)
W_c = weight of wall (kN/m)
N = vertical resultant force (kN/m)
F_r = $N \tan \delta_B + C_B B$ (kN/m)

Figure 53. Forces on an earth retaining system.

Overturning

Overturning may occur when the driving moments (generated by the lateral pressure against the wall) are in excess of the resisting moments (generated by the self-weight of the wall and wall/soil interface friction). The factor of safety against overturning is calculated by summing moments about the toe of the wall (point O, figure 53).

$$FS = \frac{\sum \text{Resisting Moments}}{\sum \text{Driving Moments}} \tag{6}$$

The minimum factor of safety against overturning is typically taken as 2.0 for walls founded on soil and 1.5 for walls founded on rock (AASHTO, 1994). The overturning criterion is not considered applicable for the design analysis of MSE walls and RSS since these systems are relatively flexible and thus the potential for failure resulting from overturning is minimal. Overturning conditions can be improved by increasing the width of the wall or, for concrete cantilever walls, relocating the wall stem towards the heel of the wall base.

In addition, for walls founded on soil, the line of action of the resultant vertical load, N, must be within the middle third of the wall base. This condition can be expressed as:

$$e \leq \frac{B}{6} \tag{7}$$

where the eccentricity, e, is the distance from the centerline of the wall to the line of action of the resultant vertical force and B is the width of the base of the wall (figure 53). Standard SI units are: e (m); and B (m). The load eccentricity is caused by the moment applied to the wall foundation resulting from the horizontal component of earth pressure. This moment induces a non-uniform pressure on the bottom of the wall foundation and, if the eccentricity is greater then B/6, can lead to loss of contact pressure between the bottom of the wall and the ground. For walls founded on rock, the allowable eccentricity must be less than B/4 (AASHTO, 1994).

Bearing Capacity

Bearing capacity failure may occur when the maximum bearing pressure along the wall base (q_{max}) exceeds the allowable bearing pressure of the wall foundation soil or rock (q_u). The factor of safety against a bearing capacity failure can be expressed as:

$$FS = \frac{q_u}{q_{max}} \tag{8}$$

The value of q_{max} can be evaluated based on the magnitude and line of action of the resultant vertical load, N (NCHRP, 1991). The value of q_u can be established using bearing capacity theory. Standard SI units are: q_{max} (kPa); and q_u (kPa). The minimum factor of safety for bearing capacity failure is typically taken as 2.0 to 3.0 (AASHTO, 1994) depending on wall type and foundation material. For RSS founded on soft soils, local bearing capacity at the toe of the slope is evaluated (FHWA-SA-96-071, 1996).

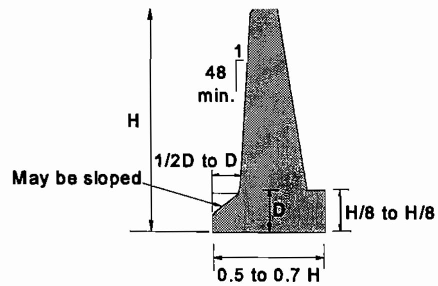
Bearing capacity can be improved by one or more of the following methods: (1) ground improvement; (2) increasing wall or slope embedment; (3) excavating weak soils and replacing with compacted fill; (4) employing staged construction techniques; and (5) increasing wall width.

Global Stability

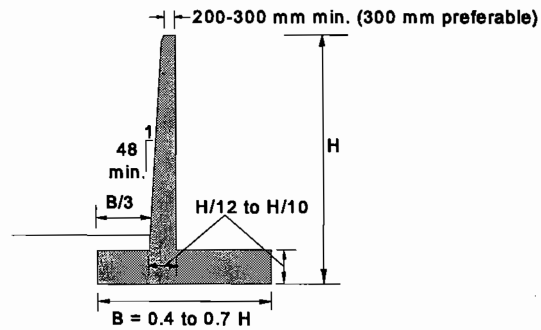
Global instability may occur if the shear stresses along a deep-seated surface under the wall exceed the soil shear strength along the same surface. Both circular and non-circular surfaces should be considered. Commercially available computer programs such as PCSTABL (Archilleos, 1988), UTEXAS3 (Wright, 1995), and XSTABL (Sharma, 1994) employ limit equilibrium analysis methods and can be used to analyze global stability. Global stability can be improved by methods similar to those used for improving bearing capacity.

Typical dimensions for rigid gravity and semi-gravity wall systems are shown in figure 54. The dimensions are based on external stability considerations assuming a range of backfill shear strengths and geometries and stable foundation soils. These dimensions can be used for preliminary design (i.e., Step (6) in table 5), but external stability calculations should be performed for final design based on the specific conditions and requirements of the project. For example, limited right-of-way in front of a cantilever wall may make geometries such as that shown in figure 55(a) necessary. Similarly, if right-of-way is restricted behind the wall, a system similar to that shown in figure 55(b) would be necessary.

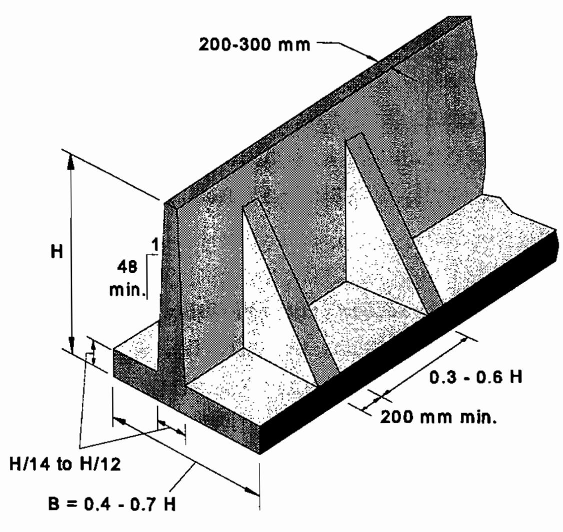
For prefabricated modular gravity wall systems, the system manufacturers typically provide tables and charts for preliminary design that are based on external stability calculations. These charts, however, are intended to be used as guidelines only for developing preliminary estimates of the required wall geometry. Detailed design using project-specific information should be carried out on a project-specific basis.



CONCRETE GRAVITY WALL



CONCRETE CANTILEVER WALL



CONCRETE COUNTERFORT WALL

Figure 54. Typical dimensions for rigid gravity and semi-gravity walls (modified after Bowles, 1982, Foundation Analysis and Design. Reprinted by permission of The McGraw-Hill Companies).

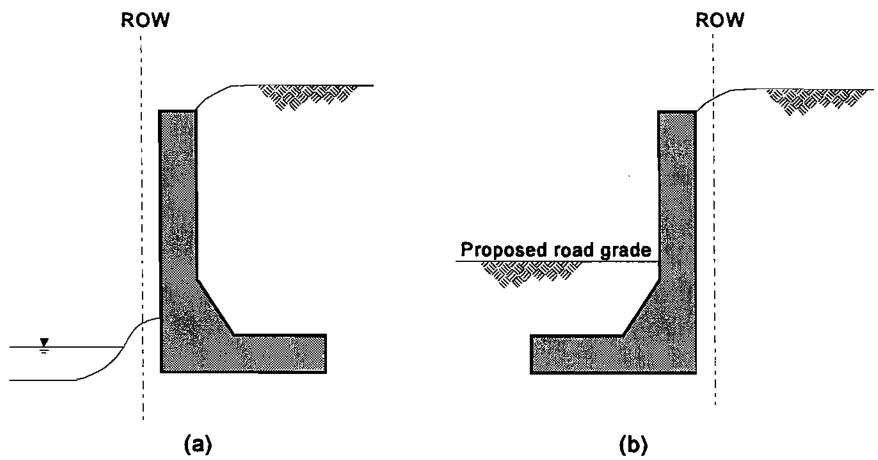


Figure 55. Cantilever wall geometries for limited right-of-way conditions.

External stability calculations are used to evaluate the required length of the reinforcement for MSE walls and RSS. Factors of safety for bearing capacity used to evaluate MSE walls and RSS may be lower than those used for the design of rigid gravity structures because MSE walls and RSS are more flexible and tolerant of differential settlements and lateral deformations. For instance, a factor of safety of 3.0 is generally used for bearing capacity for concrete cantilever walls, but a factor of safety of 2.0 can be used for MSE walls.

5.4.2.2 Backfill Soil

Ideally, backfill soil for permanent fill walls should consist of relatively free draining sands and gravels (i.e., cohesionless soils). These soils drain rapidly, are not susceptible to frost action or creep movements, and are easily placed and compacted in confined areas. In contrast, clayey soils drain slowly, are subject to seasonal volume changes, are susceptible to creep movements, and develop cracks due to shrinkage. Problems with gravity earth retaining systems have developed almost exclusively in cases where the backfill and/or the foundation consists of clayey soils (Duncan et al., 1990). The following is noted concerning the use of clayey soils as backfill for fill wall applications.

- Clayey backfills generally have lower drained shear strength than cohesionless soils. This results in: (1) larger lateral earth pressures against the back of the wall; (2) lower frictional resistance along the reinforcement for MSE walls and RSS which employ frictional reinforcement; and (3) lower bearing value for MSE walls and RSS which employ passive reinforcement.

- Clayey backfills are more plastic and contain more fines than cohesionless soils. This results in: (1) poor drainage and the potential for the development of water pressures behind the wall; (2) the potential for freezing of retained water and development of ice pressures on the back of the wall; and (3) greater potential for corrosion of metallic reinforcements for MSE walls and RSS.

- Clayey backfills have the potential to undergo creep deformations that can lead to higher earth pressures and greater wall face deformations than for soils that do not exhibit significant creep potential. Earth pressures used for design of gravity walls employing clayey backfills should be based on past performance and field experience, as wall design methods do not consider the effects of creep.

Despite these problems, silts and clays may be used as backfill soils provided suitable design procedures are employed and construction control measures are incorporated into the contract documents (AASHTO, 1994). Zornberg and Mitchell (1992) have reviewed the use of poorly draining backfill materials for MSE walls and RSS. They noted that although wall backfill drainage was enhanced when low strength, nonwoven geotextiles were used as reinforcement, their low stiffness and low strength has limited their use to low or temporary walls. Research is ongoing in evaluating and formulating a design method for MSE walls and RSS with poorly draining backfill.

Regardless of backfill type, compaction is required to obtain increased backfill shear strength and stiffness. Compaction also minimizes backfill settlement that may occur during and after construction. Compaction, however, may induce large lateral stresses against the wall, particularly near the top of the wall. A method for evaluating compaction-induced lateral stresses can be found elsewhere (e.g., NAVFAC, 1986; Foundation Engineering Handbook, Chapter 6, 1991). For walls designed for little or no movement, at-rest earth pressures plus additional pressures due to compaction-induced lateral stresses can be conservatively assumed. For more flexible walls, active earth pressures plus compaction-induced lateral stresses can be used for design.

Certain backfill soils may be considered aggressive in that they accelerate corrosion of any metallic wall components that they contact. Clayey and silty soils are generally more aggressive than more granular soils because their fine-grained nature results in high water holding capacity, poor aeration, and poor drainage. These characteristics tend to encourage corrosion. Therefore, metallic elements in these soils are more susceptible to corrosion than those in sand and gravel where there is free circulation of air (FHWA-RD-89-186, 1990). Specifications for gradation and electrochemical requirements for backfill soils are given elsewhere (Section 7.3.6, AASHTO (1994); FWHA-SA-96-071, 1996).

5.4.2.3 Wall Foundations

Wall systems should be founded on stiff, competent soil or rock whenever possible. Walls founded on less competent materials may experience structural distress due to total or differential settlement.

If a wall must be founded on less competent soil, it may be necessary to improve the soil (e.g., dynamic compaction, installation of wick drains or stone columns, etc.), excavate weak soil and replace with compacted fill material, or to support the wall with deep foundations.

Excessive differential settlement can result in structural distress and/or cosmetic damage for a number of types of wall systems. For example, concrete structures may crack excessively and metal bin walls may develop overstressed bolted connections. RSS and MSE and gabion walls are generally more flexible and are therefore better-suited to situations in which large total and differential settlements are anticipated. Even in more flexible MSE walls, however, the reinforcement/panel connection can become overstressed due to differential settlement between the reinforced soil and the wall facing panel. Flexible connections can be employed to alleviate this potential problem. Also, if significant differential settlement is anticipated, sufficient joint width and/or slip joints should be included in the design to preclude cracking of precast panels for MSE walls. Alternatively, flexible walls with flexible facing units (e.g., geotextile faced MSE walls or gabion walls) may be used for the application.

Allowable differential settlement criteria for fill walls were discussed in chapter 4. Methods that can be used to estimate settlements in clays and sands based on in-situ and laboratory test results can be found elsewhere (e.g., NCHRP, 1991; FHWA-HI-88-009, 1993).

5.4.2.4 Internal Stability and Structural Design

The internal stability of a wall system depends on the structural integrity of the wall components and connections. Examples of internal stability design issues include the size and spacing of reinforcing bars in a concrete cantilever wall and soil reinforcement elements in MSE walls. Although certain prefabricated wall systems such as gabion walls and metal and concrete bin walls have all components and connections pre-sized, the internal stability of these systems should be evaluated as part of the design analysis.

Rigid Gravity and Semi-gravity Walls

For an unreinforced concrete gravity wall, structural design consists of checking that the maximum shear, compressive, and tensile stresses acting in the wall are less than the available strength of the concrete. For a concrete cantilever and counterfort wall, the wall stem, toe, and heel are designed separately assuming each component is a cantilever beam fixed at the junction of the stem and the base. Each component is designed for bending, shear, and axial stress using standard reinforced concrete design methods (AASHTO, 1994).

Prefabricated Modular Gravity Walls

Prefabricated modular gravity walls are designed to resist the forces resulting from bin pressures inside the modules and from earth pressures behind the wall. Module members are designed for bending in both the horizontal and vertical direction between their supports. For steel member design, allowable stresses are calculated based on a net section that accounts for potential long-term losses in steel area resulting from corrosion. Allowable stress requirements for both concrete and steel module members are given in AASHTO (1994).

Mechanically Stabilized Earth Walls

The internal stability design of MSE walls principally involves the sizing and spacing of the soil reinforcing elements. The internal stability design must preclude: (1) rupture of reinforcement due to tensile overstress; (2) pull out of reinforcement from the backfill soil; (3) rupture of the connection between the wall facing and the reinforcement; and (4) distress of the facing elements under construction and service conditions.

For MSE wall design, the reinforced backfill is divided into active and resistant zones. The maximum reinforcement tension is assumed to be developed along a line separating the two zones. The location of this line for inextensible and extensible reinforcement is shown in figure 56.

The maximum tensile load transmitted to each reinforcing element (T_{max}) is required to size the element and is calculated as the horizontal stress at the elevation of each element multiplied by the tributary area of coverage of each element. The horizontal stress used to calculate the maximum tensile load in each reinforcing element depends on the value for the coefficient of horizontal earth pressure (K in figure 51) within the reinforced soil mass.

Resistance to reinforcement pullout is assumed to be mobilized along the portion of the reinforcing element extending into the resistant zone. Pullout capacity depends on the soil/reinforcement interface friction and bearing between the soil and any transverse members of the reinforcement element. Resistance to pullout is evaluated for each reinforcement level according to the following criterion:

$$\frac{\text{Pullout Capacity}}{\text{Maximum Tensile Load}} \geq FS \tag{9}$$

where FS is typically taken as 1.5. If insufficient resistance is calculated, the length of each reinforcement in the resistant zone is increased, the spacing between reinforcing elements is decreased, or other reinforcement types with better pullout characteristics are used. Pullout capacity for specific reinforcement types is calculated as described elsewhere (FHWA-SA-96-071, 1996).

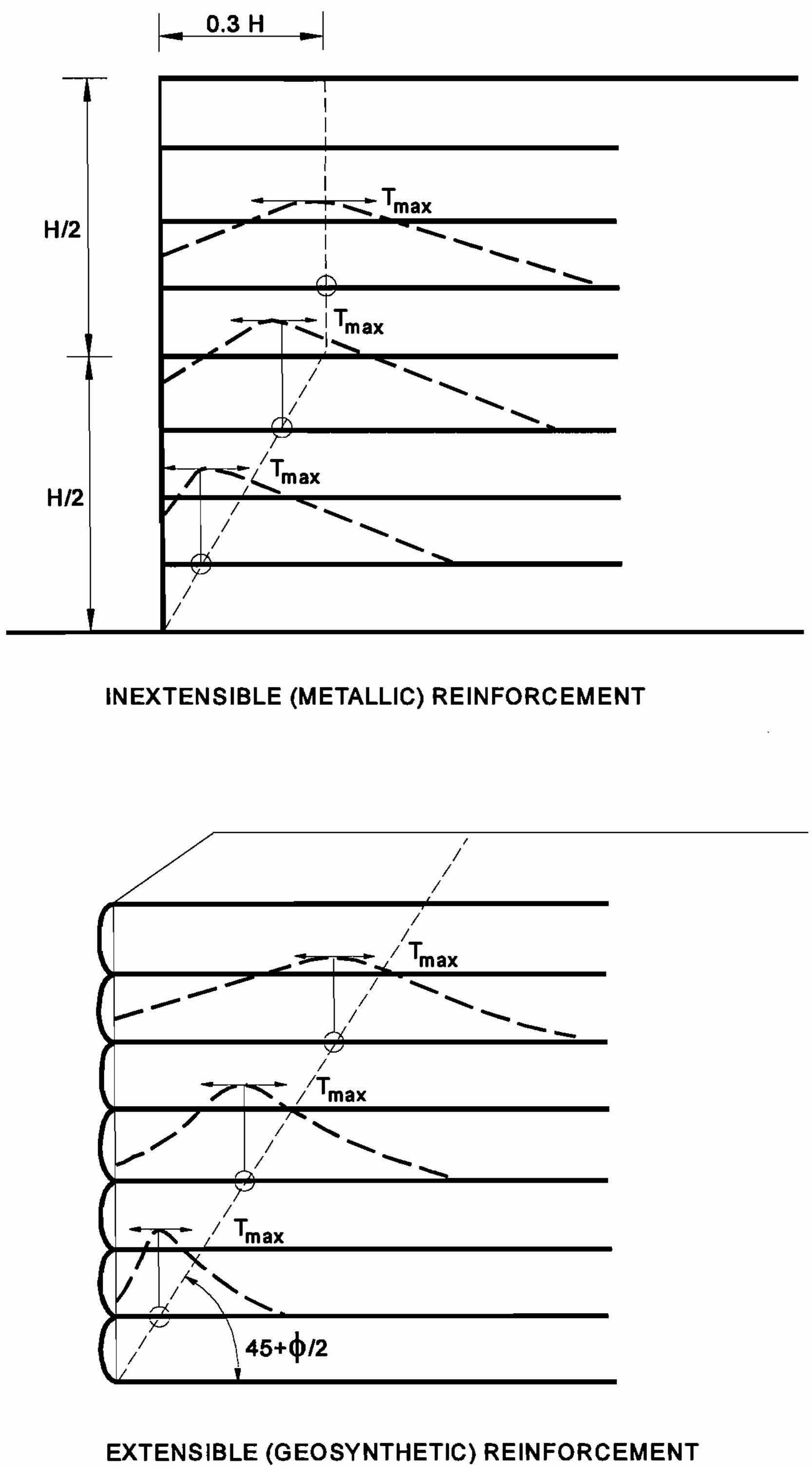


Figure 56. Active and resistant zones for MSE walls (modified after FHWA-SA-96-071, 1996)

Tensile rupture along the reinforcement is checked by comparing the allowable tensile load to the calculated maximum tensile load. For metallic reinforcement a reduced cross-sectional area is used in the calculation of allowable tensile load to account for expected material loss with time due to corrosion. For polymeric reinforcement, allowable long-term reinforcement tension is evaluated for limit states (i.e., the highest load level at which the creep-strain rate continues to decrease without failure in the reinforcement) with reductions to account for durability and construction damage. The connection of the reinforcement to the facing is checked to ensure that the tensile force in the reinforcement at the connection is not greater than the tensile strength of the connection. Procedures for calculating allowable reinforcement and reinforcement/facing connection tensile loads for MSE walls can be found elsewhere (FHWA-SA-96-071, 1996).

Reinforced Soil Slopes

The first step in the internal stability analysis of a reinforced soil slope involves evaluating the total tensile resistance, T_{total}, that needs to be mobilized in the reinforcing elements such that a minimum acceptable slope factor of safety (FS_r) can be achieved. The slope stability factor of safety is typically defined as the ratio of resisting to driving moments (or forces). The slope stability factor of safety of the unreinforced slope (FS_u) is calculated using conventional slope stability analysis techniques and assuming either circular or wedge-type slip surfaces, as appropriate. If the calculated factor of safety exceeds the minimum acceptable factor of safety, then reinforcement is not necessary and the slope is considered stable (i.e., $T_{total}=0$). If $FS_u < FS_r$, then reinforcement is necessary and T_{total} must be evaluated.

The magnitude of T_{total} is evaluated by performing slope stability analyses that incorporate tensile forces representing reinforcement layers that intersect a considered slip surface. These tensile forces increase the slope stability factor of safety by increasing the resisting moment (or force). The magnitude of T_{total} is established as the sum of tensile forces that correspond to the minimum acceptable slope stability factor of safety, FS_r. The location of the critical potential slip surface corresponding to FS_r is also obtained from the evaluation. It is noted that chart solutions for T_{total} are available for simple slope conditions (e.g., Schmertmann et al., 1987).

Once the magnitude of T_{total} is established, the second step in the internal stability analysis is to evaluate the vertical spacing of the reinforcement and required allowable stress of the reinforcement. Two alternative methods are typically used:

Method 1: The vertical spacing of the reinforcement is assumed based on project requirements such as minimum backfill lift thickness or constraints imposed by the facing. The spacing assumption yields the number of reinforcement layers present in the slope. The required strength of each layer is calculated as T_{total} divided by the number of reinforcement layers. This required strength is compared to the allowable stress for the particular type of reinforcement.

Method 2: The number of reinforcement layers required is calculated as the ratio of T_{total} to the allowable stress of each reinforcement. The vertical spacing of the layers is then dictated by the required number of layers and the slope height.

For simplicity of design of low slopes (i.e., slopes less than 6 m in height), T_{total} is usually assumed to be equally distributed to each layer of reinforcement. For higher slopes, T_{total} is assumed to be represented by a triangular earth pressure distribution. For this latter case, the slope is typically divided into two or three zones of equal height with uniform reinforcement type and vertical spacing within each zone. A lower zone may have a closer spacing for reinforcement layers compared to the upper zone, or the reinforcement spacings may be uniform throughout the slope with stronger reinforcement used in the lower zone. Recommendations on the appropriate distribution of reinforcement can be found in FHWA-SA-96-071, (1996).

The embedment length of each reinforcement layer beyond the critical potential slip surface corresponding to T_{total} is checked by calculating the factor of safety against pullout in the same manner as for MSE walls. If insufficient resistance is calculated, the length of the reinforcement is increased. The length of the reinforcement should also be adequate to extend beyond all potential slip surfaces for which $FS_u < FS_r$.

5.4.3 Cut Walls

5.4.3.1 Earth Pressure Diagrams

The earth pressure distribution that develops on a cut wall varies with the in-situ soil shear strength, method and sequence of wall construction, and overall wall stiffness (i.e., stiffness of wall and other lateral restraint components such as anchors). These factors affect the magnitude of lateral wall deformation that occurs during construction. Some relatively flexible walls such as sheet-pile or soldier pile and lagging walls can be expected to undergo lateral deformations sufficiently large to induce active earth pressures. For design of these systems, theoretical active earth pressure diagrams using either Rankine or Coulomb analysis can be used.

For stiffer wall systems such as anchored or braced walls, the deformation pattern is more complex and not consistent with the development of a theoretical Rankine or Coulomb distribution. A typical deformation pattern for an anchored wall is shown in figure 57. The stiffness, inclination, vertical spacing, and time and method of installation of the supports directly influence the deformation pattern and the earth pressures acting on this type of wall. The apparent earth pressure diagrams (figure 58)

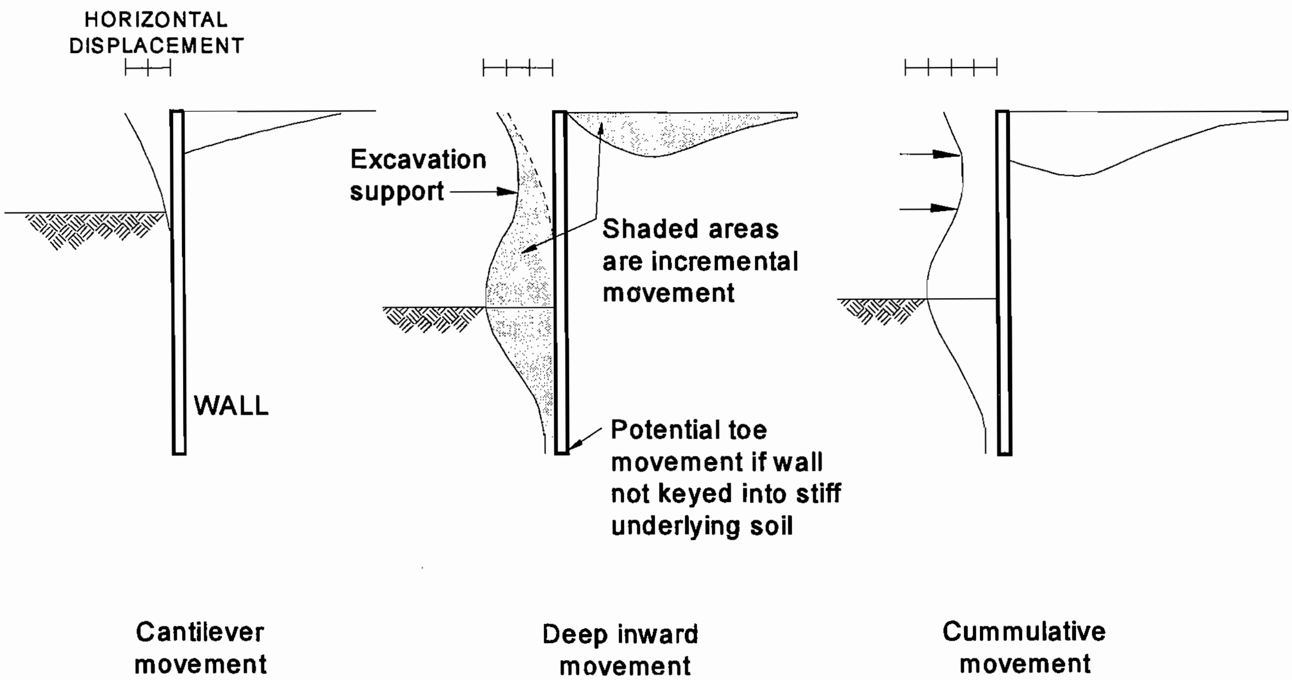
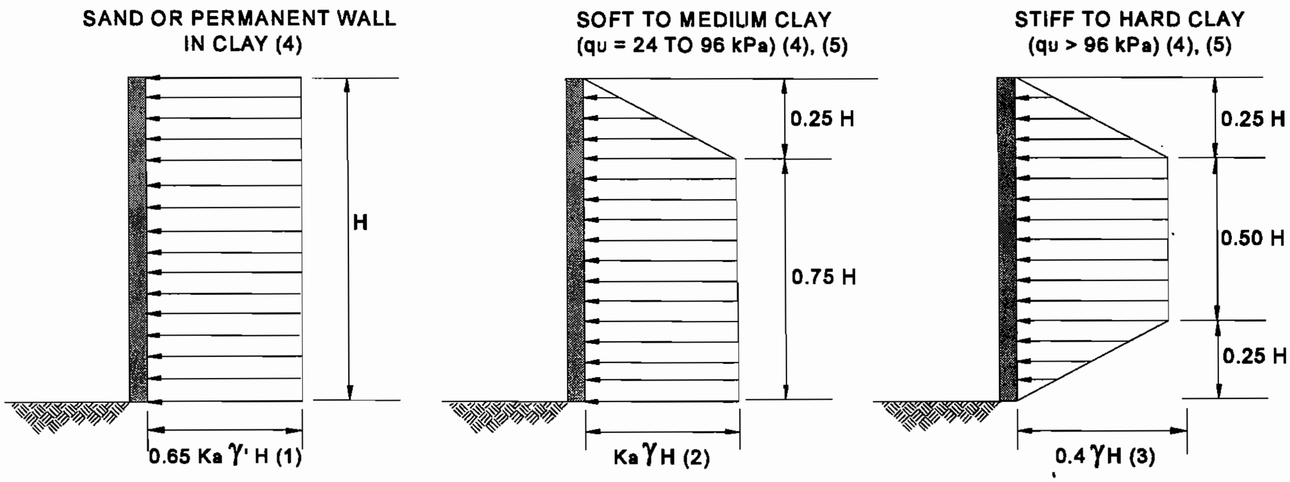


Figure 57. Patterns of movement for braced or anchored walls (modified after Clough and O'Rourke, 1990, Construction Induced Movements of Insitu Walls, Geotechnical Special Publication No. 25. Reprinted by permission of ASCE).

developed by Terzaghi and Peck (1967) are semi-empirical earth pressure diagrams commonly used for designing both anchored and braced walls. These diagrams represent conservative envelope values back-calculated from field measurements of strut loads in braced excavations and they account for a wide range of field conditions, soil types, and construction practices as well as theoretically predicted behavior.



NOTATIONS:

H =	final wall height (m)
K_a=	active earth pressure coefficient (dimensionless)
γ', γ=	effective and total soil unit weight (kN/m^3)
m=	reduction factor (dimensionless)
q_u=	unconfined compressive strength (kPa)

Notes:

(1) $K_a = \tan^2(45 - \phi/2)$

(2) $K_a = 1 - m(2q_u/\gamma H)$

m=1 (overconsolidated clays)

m=0.4 (normally consolidated clays)

(3) Value of 0.4 should be used for long-term conditions
Value of 0.2 to 0.4 may be used for short-term conditions.

(4) Surcharge and water pressures must be added to these diagrams.

(5) Diagrams are not valid for permanent wall systems or wall systems where water level lies above bottom of excavation.

Figure 58. Terzaghi and Peck apparent earth pressure diagrams for braced and anchored walls (modified after Terzaghi and Peck, 1967, Soil Mechanics in Engineering Practice. Reprinted by permission of John Wiley and Sons, Inc).

5.4.3.2 Corrosion Protection of Anchors and Soil Nails

As part of the design of an anchored wall or a soil-nailed wall, proper measures to prevent corrosion of the anchors or soil nails must be considered. The type of corrosion protection employed will depend on the aggressiveness of the soil environment, the proposed design life of the structure, the risk associated with the failure of an anchor or soil nail, and the cost of the protection measures. Experience pertaining to corrosion in the anchor length of permanent ground anchors is appropriate for evaluating corrosion susceptibility for soil nailing applications. The mechanism of corrosion, identification of corrosive soil environments, requirements for field testing, and case studies of field corrosion problems are discussed in FHWA RD-82-047 (1982) and FHWA DP-68-1R (1988).

Forms of corrosion protection for the anchor length include grout-protected anchors and encapsulated anchors. Grout-protected anchors (single corrosion protection) rely on a specified thickness of grout (usually at least 100 mm) around the tendon, bar, or strand to inhibit corrosion, whereas encapsulated anchors (double corrosion protection) rely on complete coverage of the grout-protected anchor with either a corrugated plastic or steel tube.

The area around and including the anchor head of an anchor is most susceptible to corrosion due to the combined effects of stress concentrations due to the gripping mechanism employed in stressing the anchor and the availability of oxygen near the wall face (FHWA DP-68-1R, 1988). In several reported cases of anchor failure, the failure occurred as a result of corrosion within 2.0 m of the anchor head (Anderson, 1984). Typically, the anchor head is protected by constructing an enclosure over the end of the unbonded tendon (see figure 31) and filling it with grout or anti-corrosion grease (FHWA-RD-82-047, 1982).

5.4.3.3 Internal Stability and Structural Design

Non-gravity Cantilevered Walls

Non-gravity cantilevered walls resist lateral load through a combination of flexural resistance of the vertical wall elements and passive soil resistance developed through wall embedment below final excavation depth. A preliminary estimate of the design depth of embedment can be made based on the relative density of the soil below the excavated depth; that is, shallower depths of embedment can be used for wall construction in more competent soils as compared to weaker soils that require greater depths of embedment. Approximate penetration depths for different soil relative densities for the case of cantilevered sheet-pile walls in cohesionless soils are given in table 6. Typically, it is assumed that the maximum bending moment occurs above the excavation depth, but if large movements are expected, as in the case for excavations in soft clays, the loading on the embedded portion of the wall may control design.

For the case of non-gravity cantilevered walls with discrete vertical elements (e.g., soldier pile and lagging wall), design calculations differ somewhat from sheet-pile walls in that passive soil resistance below final excavation depth develops only at the soldier pile locations. Design is typically performed assuming that the effective width of each soldier pile is up to three times its actual width (AASHTO, 1994). This assumption reflects the fact that some passive resistance is mobilized in the soil between the soldier piles. For soldier pile embedment in soft clays or very loose sands, less passive resistance is available and the effective width is decreased accordingly.

Table 6. Approximate penetration depths for cantilevered sheet-pile walls (after NAVFAC, 1986) .

SPT (N) blows/300 mm	Relative Density	Depth of Embedment
0 - 4	very loose	2.0H[(1)]
5 - 10	loose	1.5H
11 - 30	medium dense	1.25H
31 - 50	dense	1.0H
>50	very dense	0.75H

Notes: (1) H is the height of the wall above final excavated grade

Anchored Walls

The design of an anchored wall includes choosing an appropriate earth pressure diagram to estimate anchor loads, evaluating the local stability at the level of each anchor, and evaluating the global stability of the wall system. An anchored wall relies upon the transfer of resisting tensile forces, generated in the anchors, into the ground behind the wall through friction (adhesion) mobilized at the anchor/ground interface (figure 59). The resisting tension force is mobilized by prestressing the anchor to the design load after its installation.

Local anchor stability is evaluated in terms of the factor of safety against anchor breakage (in tension) or pullout. Calculations to check breakage are similar to those for reinforcement in MSE walls where the maximum tensile load in the anchor must be less than the allowable tensile load. Maximum anchor tensile loads are typically obtained from the semi-empirical earth pressure diagrams of Terzaghi and Peck (figure 58) (see FHWA DP-68-1R, 1988). Many contractors use similarly shaped diagrams with different values for the earth pressure ordinate that are based on field measurements of anchor tension loads in previously constructed anchored wall systems in similar soils.

Adequate design against pullout requires that sufficient frictional resistance be developed in the anchor bond zone. The pullout resistance of each anchor is a function of the size and shape of the drill hole, strength characteristics and density of the soil in which it is placed, drilling method, length tested, method used to clean the drill hole, and the grouting method or pressure used (FHWA DP-68-1R, 1988). Estimates of pullout capacity of anchors are mainly based on empirical values or field experience. Table 7 provides a summary of estimated ultimate interface lateral shear resistances for anchors as a function of soil type and method of installation. These values can be used to make preliminary design capacity estimates.

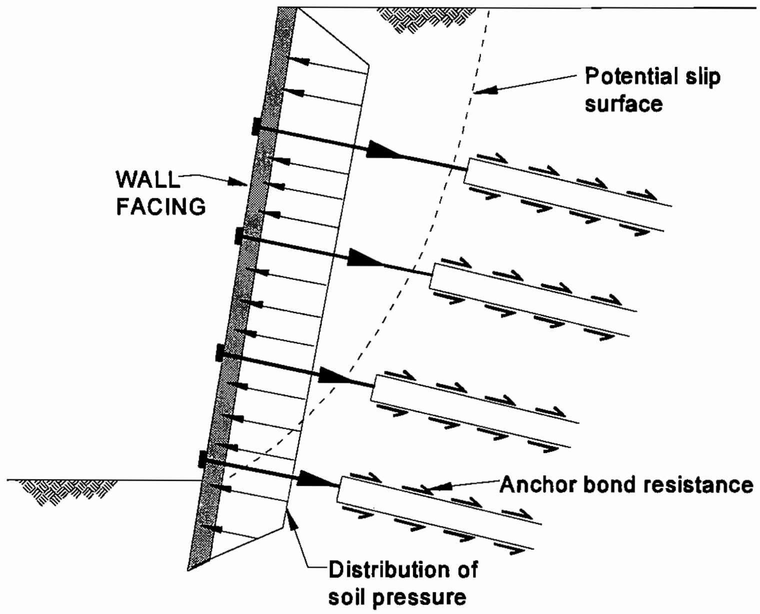
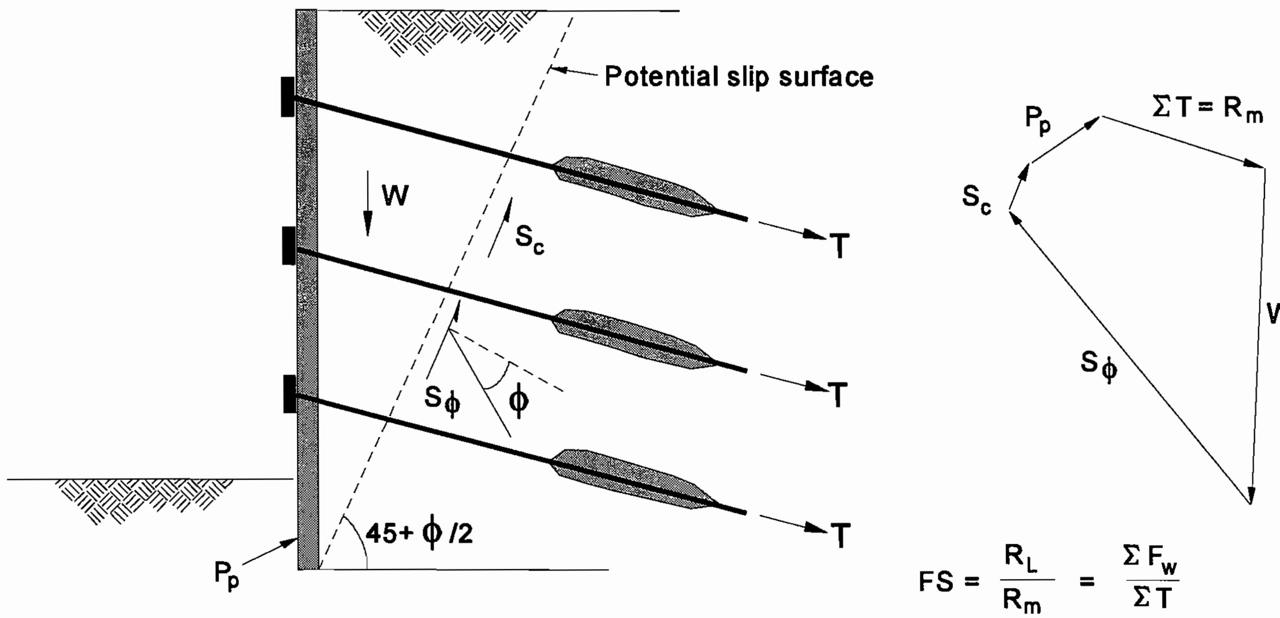


Figure 59. Load transfer mechanism in ground anchors (modified after Foundation Engineering Handbook, Chapter 26, 1991. Reprinted by permission of Chapman and Hall).

The evaluation of the global stability of an anchored wall involves calculation of factors of safety of the wall system and surrounding ground with respect to a rotational or translational failure along a potential sliding surface. Two modes of global instability are checked as part of the detailed design. They include: (1) overall external stability; and (2) pullout failure of the entire anchor system. Conventional limit equilibrium methods for slope stability can be used to evaluate overall external stability. These analyses are particularly important for evaluating wall systems for which nearby structures on shallow foundations exist or for situations in which soft soils exist below the wall. Pullout failure of the entire anchor system must also be checked to ensure that sufficient tensile resistance is developed in the bond zone to resist a wall-anchor failure (e.g. figure 60). The evaluation of pullout failure of the anchor system includes a determination of the geometry and position of a critical potential sliding surface. The position of this critical surface is used to specify the free length of the anchor. To account for variations in forming the anchor bond length, the free length is extended to 1.5 m beyond the critical surface or to a distance equal to one-fifth of the wall height, whichever is greater.

Anchors also induce a vertical load on the wall. For steeply inclined anchors, it should be ensured that sufficient bearing capacity can be developed below the wall to support the downward force.



NOTATIONS:

- W: weight of soil mass (kN/m)
- S_ϕ: frictional component of soil strength (kN/m)
- S_c: cohesive component of soil strength (kN/m)
- P_p: passive earth pressure resultant force (kN/m)
- T: anchor force (kN/m)

Figure 60. Global stability analysis for an anchored wall (modified after Foundation Engineering Handbook, Chapter 26, 1991. Reprinted by permission of Chapman and Hall).

Soil-Nailed Walls

The design of a soil-nailed wall includes an evaluation of local and global stability. A locus of maximum tensile forces in the nails separates the nail-reinforced mass into an active zone and a resistant zone (figure 61). In the active zone, lateral shear stresses are mobilized at the perimeter of the nail to restrain the outward ground movement, and, in the resistant zone, nail tension forces are transferred into the ground behind the wall.

Several design methods exist for soil-nailed walls. Each is based on limit equilibrium concepts wherein it is assumed that a failure surface can develop within the reinforced zone (internal failure), outside the reinforced zone (external failure), or partially within the reinforced zone (mixed failure) (see figure 62). Potential failure surfaces with different shapes are considered. These equilibrium approaches can be used to evaluate a global factor of safety that is defined as the ratio of resisting forces to driving forces, or, alternatively, partial factors of safety can be applied to soil shear strength, nail tensile resistance, and nail pullout resistance. The specified minimum values of these partial factors of safety vary significantly among the different design methods.

Table 7. Ultimate lateral resistance for soil nails and anchors (modified after Foundation Engineering Handbook, Chapter 26, 1991. Reprinted by permission of Chapman and Hall).

Construction Method	Soil Type	Soil Nails(1)	Anchors(1)
Rotary drilled	Silty sand Silt Piedmont residual	30 to 59 18 to 23 22 to 37	73 to 131
Driven casing	Sand Dense sand/gravel Dense moraine Sandy colluvium Clayey colluvium	88 117 117 to 175 29 to 58 15 to 30	102 to 190 146 to 292
Jet grouted	Fine sand (medium dense) Sand Sand/gravel	 117 292	51 to 66 66 to 124 124 to 168
Augered	Soft clay Stiff to hard clay Clayey Silt Calcareous sandy clay Silty sand fill	6 to 9 12 to 18 15 to 29 58 to 88 6 to 9	 29 to 58 22

Notes: (1) Values for ultimate lateral resistance are in kN/m.

The internal stability design of a soil-nailed wall involves the sizing and spacing of the soil nails. The overall approach includes: (1) computing the required total nail reinforcing force to achieve a specified factor of safety; (2) developing a nail spacing for which there is sufficient nail cross-sectional area to ensure that the required nail force can be provided without breakage of a nail or failure at a nail head; and (3) determining nail lengths such that there is sufficient nail length behind potential failure surfaces to prevent nail pullout. The nail/soil bond strength is estimated for design (see table 7) and it is usually verified in the field through nail pullout tests (FHWA-SA-96-069, 1996). As with anchored walls, calculations to check breakage account for corrosion and are similar to those performed for MSE walls.

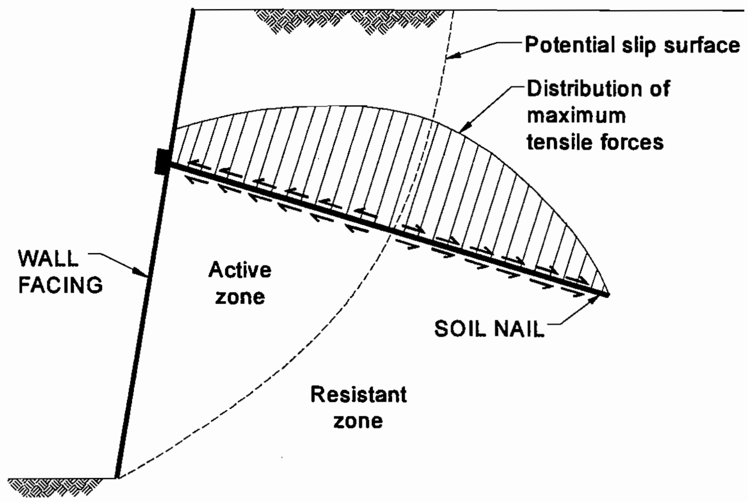


Figure 61. Load transfer mechanism in soil nails (modified after Foundation Engineering Handbook, Chapter 26, 1991. Reprinted by permission of Chapman and Hall).

Micropile Walls

The design of micropile walls is based on the general premise that the micropiles and the retained soil between the micropiles act as a composite structure that together resist lateral earth pressures. Each micropile is extended below potential failure planes and serves to physically connect, or anchor, the potentially unstable soil mass to the underlying stable mass.

Root-pile walls employ numerous small diameter CIP micropiles that are closely spaced. The assumption is made for design that micropile spacing is close enough such that the wall forms a coherent mass that acts as a rigid gravity wall (figure 63). The shear stresses on any potential sliding surface through the coherent mass must be resisted by the allowable shear stresses of the micropile-soil combination with some prescribed factor of safety.

Insert Walls^{SM} also employ a network of vertical and battered micropiles, but they are spaced farther apart than for a root-pile wall. Like root-pile walls, Insert Walls^{SM} are designed to resist lateral earth pressures. The mechanism by which they achieve this goal is thought to be somewhat different than the mechanism for gravity root-pile walls. Insert Wall^{SM} performance data have indicated that wall movements are typically concentrated along a thin, localized plane. The implication is that these walls are relatively flexible and do not behave as rigid gravity walls. The design procedure for Insert Walls^{SM} includes: (1) conducting stability analyses to evaluate the resistance to lateral stresses along

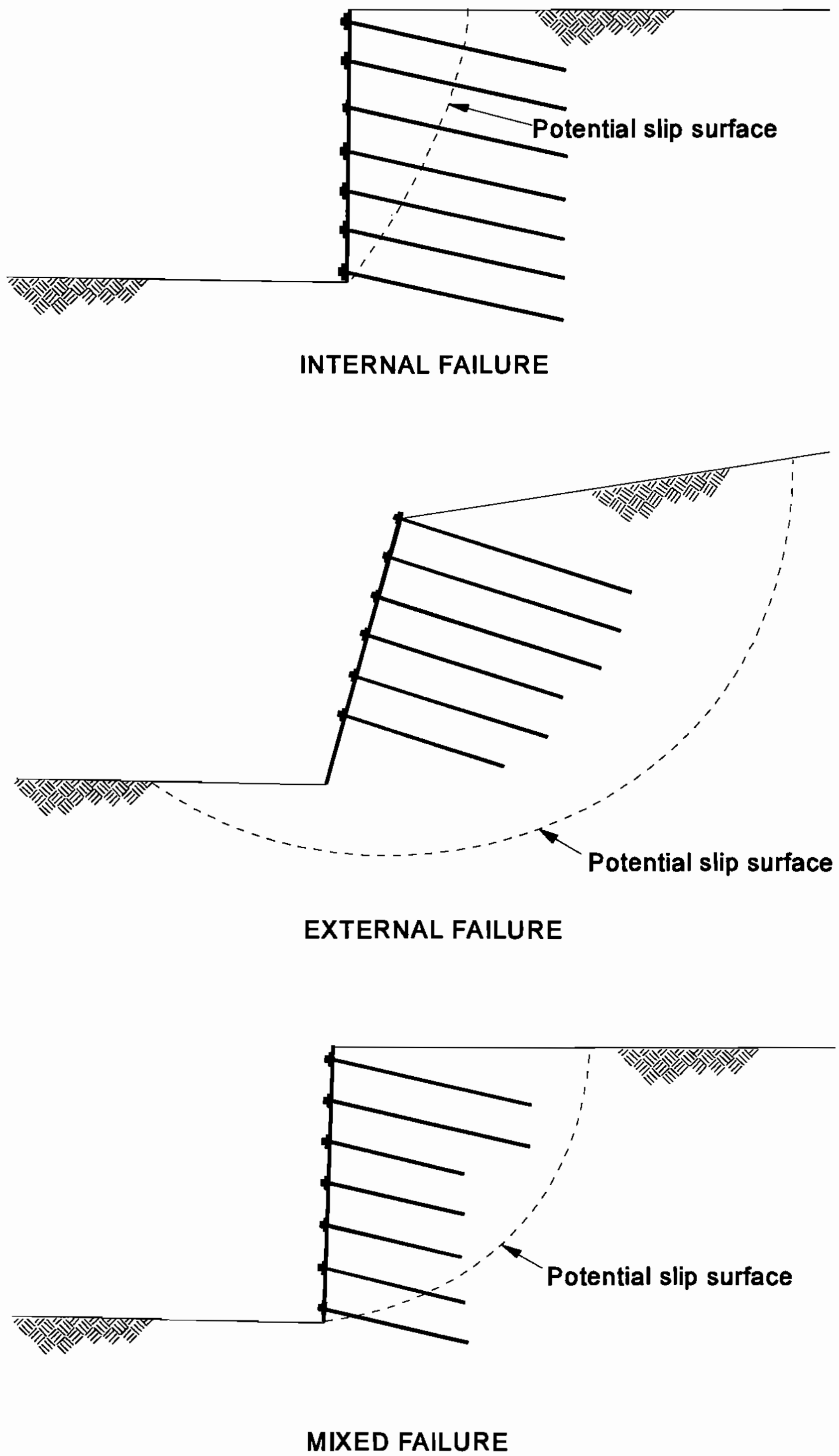


Figure 62. Failure conditions to be analyzed for soil-nailed walls (modified after FHWA-PL-93-020, 1993).

a potential or existing sliding surface required to provide a certain factor of safety; (2) checking the potential for structural failure of the micropiles due to the lateral stresses; and (3) evaluating the potential for soil movement around the micropiles (Pearlman et al., 1992).

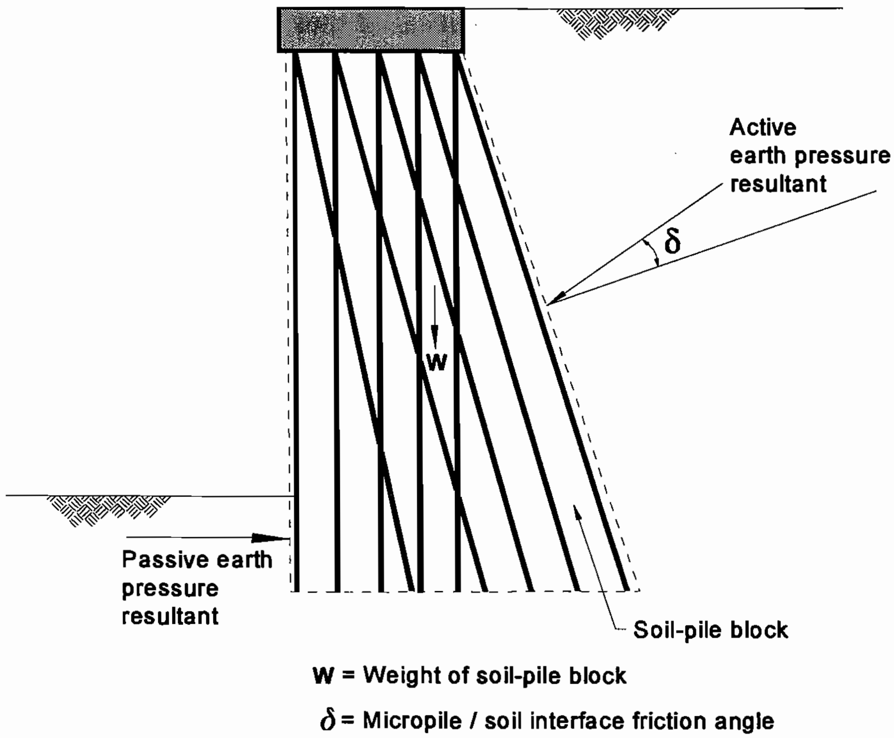


Figure 63. Forces on a root-pile wall (modified after Lizzi, 1978, Reticulated Root Piles to Correct Landslides, ASCE Convention and Exposition, Chicago. Reprinted by permission of ASCE).

5.5 OTHER DESIGN ISSUES

5.5.1 General

Several additional issues are frequently encountered in the design of both fill and cut wall systems. These include the following: (1) evaluating the appropriate depth of embedment of the wall below grade (fill walls) or below the bottom of the excavation (cut walls); (2) design and construction of drainage systems for backfill and retained soils; (3) design for potential earthquake loading; and (4) locating wall appurtenances and evaluating their influence on the design and construction of a wall system. As discussed in this section, the significance of these issues in the design process depends on site-specific conditions, wall application, and wall type.

5.5.2 Wall Embedment

The depth of wall embedment is a critical design issue for some site conditions and wall systems. In other situations, however, it may be selected based on typical values. With fill wall systems, the depth of wall embedment below grade is most critical at sites where the depth of seasonal volume change is large or where the wall is located near the edge of a waterway where scour may result in wall instability. For cut walls, the depth of embedment below the bottom of the excavation is usually a critical design issue since embedment stabilizes the wall through the development of passive soil resistance. Embedment depth can also be significant for cut walls if it is necessary to extend the wall downward into the foundation soil to act as a seepage barrier.

With respect to wall stability, greater embedment depths allow for development of greater passive soil resistance in front of the wall. This results in increased external wall stability. For fill wall systems, however, this passive resistance is generally neglected due to the possibility that the soil in front of the wall may not remain permanently in place. For cut wall systems, determination of the depth of wall embedment is a major design issue because the passive resistance developed below the level of the excavation is the sole stabilizing force for non-gravity cantilevered wall systems and is a major stabilizing force for anchored wall systems.

Wall embedment may be necessary for both fill and cut wall systems to provide adequate bearing capacity. For a fill wall, it may be necessary to construct the wall foundation below the ground surface to increase bearing capacity. Anchored walls with inclined anchors will generate vertical loads when prestressed to design loads. These vertical loads must be resisted by the vertical wall elements through frictional and point resistance developed below the depth of the excavation. These components of resistance typically increase with increasing embedment depth.

Walls need to be founded below the depth of seasonal volume change to minimize the cosmetic damage that can result from foundation swelling or subsidence. In extreme cases, foundation swelling/subsidence can result in structural damage. This issue is only of concern for fill walls. The most common seasonal volume change affecting walls results from soil freeze/thaw cycles and frost heave. Walls constructed in cold climates should be founded below the frost line to avoid damage. It is noted that frost heave generally occurs only in partially saturated silts and sandy silts, though occasionally in low plasticity clays. Seasonal volume change may also occur in soils susceptible to expansion and collapse. With these soils, local experience usually dictates appropriate design measures.

Walls constructed in and along waterways are subject to erosion (scour) that can result in failure of the wall due to undermining. Scour is a function of the direction, curvature, and velocity of water currents. When scour is expected, cutoff walls and/or riprap and associated filter materials should be employed in the design to protect the toe of the wall. Details related to the prediction and evaluation of scour can be found elsewhere (FHWA-IP-90-017, 1995).

5.5.3 Wall Drainage Systems

5.5.3.1 Introduction

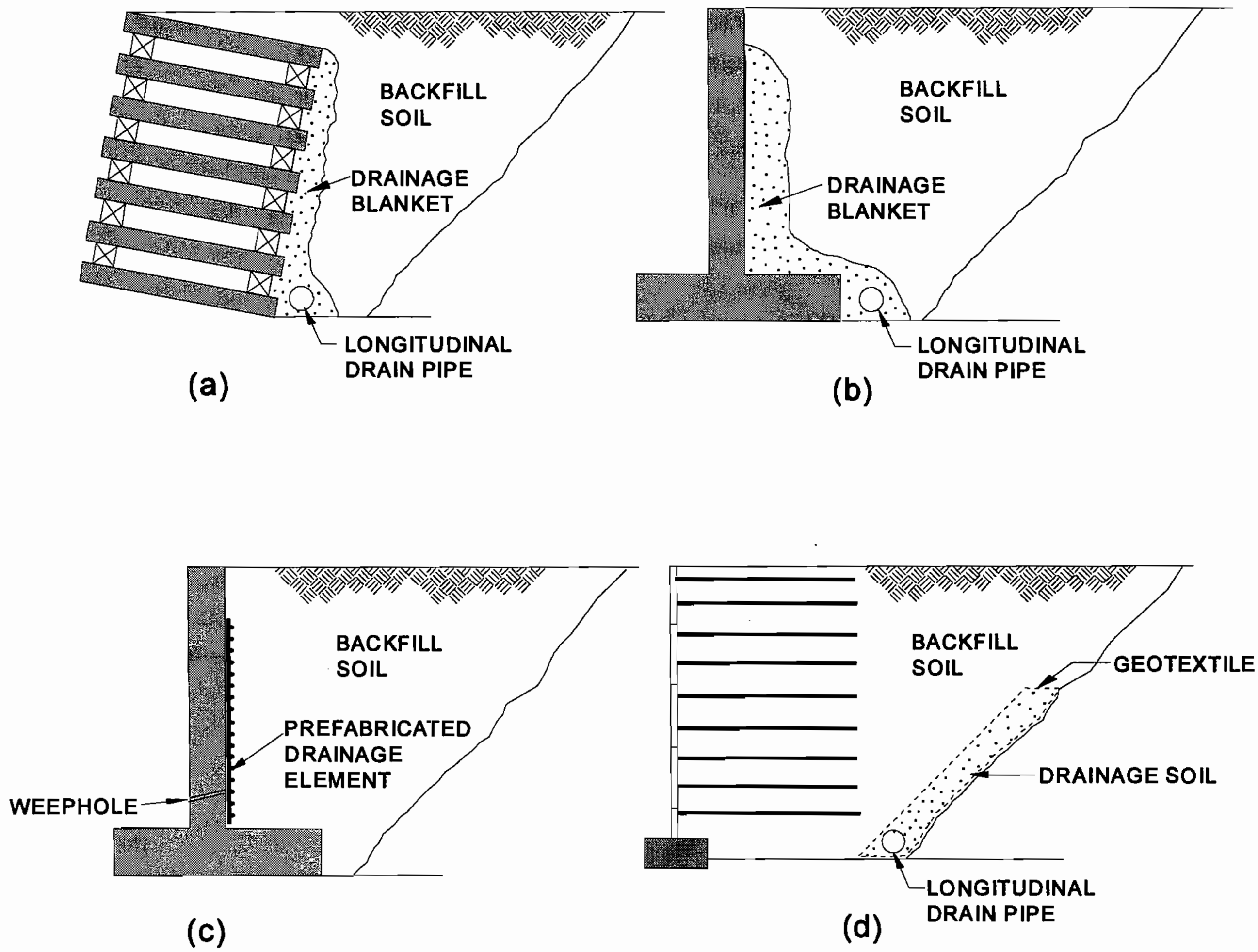
A factor which has resulted in the unsatisfactory long-term performance of earth retaining systems is inadequate drainage of the wall backfill and/or retained soil. Unless a wall system is designed to resist full potential water pressures, appropriate drainage measures must be included. Drainage systems serve to prevent the accumulation of destabilizing water pressures which may develop as a result of ground-water seepage and/or infiltration of surface water. Other detrimental effects resulting from poor drainage may include: (1) excavation face instability; (2) decreased shear strength of retained soils and soil interfaces; and (3) corrosion of metallic components.

Drainage system design depends on wall type, backfill and/or retained soil type, and ground-water conditions. Drainage system components (e.g., granular soils, prefabricated drainage elements, filters) are usually sized and selected based on local experience, site geometry, and estimated flows, although detailed design is occasionally performed. Drainage systems may be omitted if the wall is designed to resist full water pressure. This approach is used primarily in cases where the project requires that the wall system be watertight (e.g., where ground-water drawdown in the retained soil is prohibited or undesirable). Drainage systems are also occasionally used to maintain reasonably constant moisture conditions in soils near the wall that are susceptible to volume change upon wetting/drying (i.e., expansive or collapsible soils). Drainage systems for fill and cut wall systems are typically designed using one or more of the following components: (1) free-draining granular soil backfill; (2) sloping or horizontal drains; and (3) vertical drains.

5.5.3.2 Drainage Systems for Fill Walls

The most effective means of providing drainage for a fill wall is to use free-draining granular soil for the wall backfill, thus allowing the entire backfill mass to serve as a drain. Since it may be costly to obtain free-draining material for some project applications, it may be necessary to construct other types of drainage systems. Typical drainage systems for fill walls are shown schematically in figure 64. The drainage systems shown include: (1) a column of clean coarse sand placed just behind the back of the wall (figure 64(a)), or behind the back of the wall and over the wall base (figure 64(b)); (2) prefabricated drainage elements placed against the back of the wall (figure 64(c)); and (3) a drainage blanket constructed against the backslope of the wall excavation (figure 64(d)).

Vertical drains (see figures 64(a), 64(b), and 64(c)) reduce water pressures against the back of the wall resulting from ground-water seepage. The drainage system shown in figure 64(d), however, is more effective in reducing water pressures as opposed to vertical drains since it permits drainage to occur before ground-water seepage can enter the backfill. This system typically consists of either coarse aggregate with a geotextile filter or a drainage geocomposite. Drainage geocomposites are well-suited to fill wall applications where the excavation backslope is steep or nearly-vertical; under these conditions, a coarse aggregate drainage blanket is difficult to construct.



Note: Requirements for location, extent, and material properties of wall drain systems will depend on wall type, cut/fill limits, ground-water conditions, and wall function and design life.

Figure 64. Drainage systems for fill walls.

Appropriate drainage measures to prevent surface water from infiltrating into the wall backfill should be included in the design of a wall system. During construction, the backfill surface should be graded away from the wall face at the end of each day of construction to prevent water from ponding behind the wall and saturating the soil. When final backfill grades are reached, a low permeability soil should be placed over the top of the wall backfill as a means to limit infiltration. The ground surface above the wall is then graded towards collection components such as concrete, asphalt, or vegetation lined swales or ditches. These collection components also serve to prevent surface water from overtopping the wall. Where significant use of potentially corrosive de-icing salts is anticipated, relatively impervious barriers such as geomembranes may be constructed just above the backfill. For permanent RSS, facing systems should be selected to minimize erosion resulting from rainfall and surface-water runoff.

Typical conveyance components of drainage systems include: (1) longitudinal drain pipes with periodic outlet pipes; and (2) weepholes. Both types of conveyance components are illustrated in figure 64. Longitudinal pipes transport collected water to outlet pipes that discharge at appropriate points in front of the wall. These pipes need to be large enough and sufficiently sloped to effectively drain water from behind the wall while maintaining sufficient pipe flow velocity to prevent sediment buildup in the pipe. Weepholes consist of holes that extend through the wall facing and are closely spaced (typically less than 3 m apart) both vertically and horizontally along the wall. Water that collects against the wall facing flows through the weepholes and discharges down the front of the facing. Weepholes need to be protected from clogging with a gravel pocket or a geotextile filter in the soil backfill. Non-continuous wall facings such as stacked masonry blocks or precast concrete panels do not require weepholes, as water can discharge through the gaps between facing elements.

5.5.3.3 Drainage Systems for Cut Walls

The need for drainage in cut wall system applications varies with project requirements. Drainage systems may be omitted in cases where ground-water drawdown in the retained soil is prohibited or undesirable. In other cases, drainage is used as a means to control surface-water infiltration and ground-water seepage. Other beneficial effects of drainage include:

- allowing excavations to be constructed in relatively dry conditions;
- reducing seepage so that instabilities such as soil heave at the base of the excavation, soil softening due to saturation, or piping of materials at the wall face is minimized;
- reducing water levels which increases passive resistance of the soils below the excavation depth; and
- enabling anchors and soil nails to be installed without the use of special drilling and grouting techniques (ASCE, 1994a).

Surface drainage is usually achieved by directing water away from the wall face either by grading or by collecting and transporting surface water in ditches or pipes. To minimize surface water that can enter the excavation during construction and weaken the soils inside the excavation, dikes can be constructed on the ground surface near the top of the wall or the vertical wall element can be extended above the ground surface grade.

For cut wall systems, collection of subsurface flow is usually achieved with prefabricated drainage elements placed between the wall and the permanent facing. With this type of system, vertical drainage strips are extended over the full height of the wall. Single strips can be placed at appropriate horizontal spacings along the wall or a continuous sheet can be placed over the entire wall face, depending on the project drainage requirements and the expected flow rate. Water intercepted in the drainage elements flows downward to the base of the wall where it is conveyed through the permanent facing in longitudinal/outlet pipes or weepholes. In other applications, the drainage elements are extended into the subgrade to a footing drain. Similar drainage systems may be used for face drainage of soil-nailed walls where the prefabricated drainage elements are typically placed between the excavated face and the back of the shotcrete facing layer. A drainage system for a soil-nailed wall is shown schematically in figure 65.

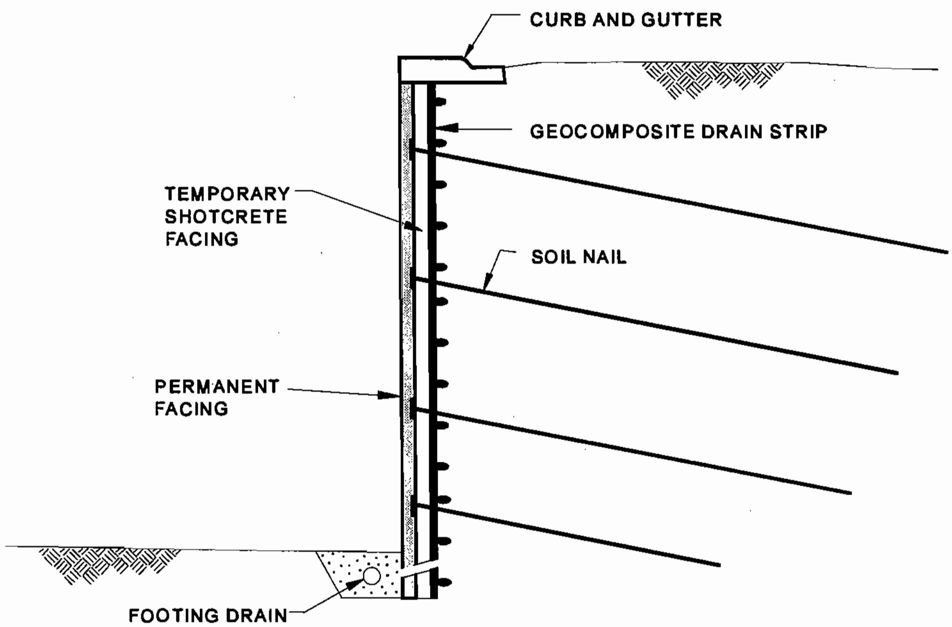


Figure 65. Drainage system for soil-nailed wall (modified after FHWA-SA-93-068, 1994).

In applications where subsurface flow rates are large, horizontal drains may be used to remove water from behind the wall. A horizontal drain is a small diameter perforated pipe that is advanced into a nearly horizontal drill hole in an existing slope. For example, a cut wall constructed on or at the base of a steep slope will likely interfere with pre-existing natural drainage paths. This interference may cause hydrostatic pressures resulting from trapped water to build-up against the wall. To relieve these pressures, horizontal drains can be installed at appropriate vertical and horizontal spacing along the wall alignment. For wall system applications, horizontal drains extend back from the wall face a sufficient distance to intercept subsurface flow before it enters the retained soil mass.

5.5.4 Seismic Wall Design

Earth retaining systems must be designed to resist both static lateral earth pressures and seismically-induced dynamic earth pressures. The seismic design of most wall systems is based on a pseudo-static external stability analysis originally proposed by Mononobe (1929) and Okabe (1926). This analysis can be used to estimate the equivalent static earth pressure produced by the dynamic horizontal forces resulting from horizontal seismic accelerations. The analysis assumes that sufficient lateral wall movement occurs during a seismic event to fully mobilize peak soil strengths in the backfill or retained soil.

A key parameter for the Mononobe-Okabe analysis is the horizontal seismic acceleration. A contour map of horizontal seismic accelerations is presented in Division I-A - Seismic Design Commentary (AASHTO, 1994). The magnitude of the seismic acceleration is reported as a percentage of gravity and ranges from zero to 60 percent. These magnitudes depend on the seismic risk associated with particular geographic locations.

In the AASHTO (1994) specifications, recommendations are given with respect to the magnitude of the horizontal seismic acceleration for use in design. With AASHTO procedures, the acceleration obtained from figure 66 is scaled based on the type of wall system and the magnitude of acceptable lateral wall deformation. Vertical seismic accelerations are not included in the analysis. For example, for rigid gravity and semi-gravity walls, prefabricated modular gravity walls, and non-gravity cantilevered walls, the horizontal seismic acceleration for use in the Mononobe-Okabe analysis is reduced by fifty percent from that shown on the horizontal acceleration contour map. According to Elms and Martin (1979), this value is adequate for most design purposes provided allowance is made to allow the wall to move laterally a sufficient amount. For walls that are designed to be unyielding, such as bridge abutements restrained by batter piles or for anchored walls, AASHTO procedures call for the horizontal seismic acceleration from figure 66 to be increased by 50 percent. This type of design may lead to oversized wall components (AASHTO, 1994), so it is preferable to design a wall for a small amount of seismically-induced lateral deformation.

The seismic design of MSE and soil nailed walls is also based on the Mononobe-Okabe method for evaluating external seismic stability. An internal seismic stability analysis is also performed as part of the design of these wall systems. This analysis incorporates the effects of the inertial force generated by the reinforced soil volume during a seismic event. The reinforcing elements must have sufficient length and cross-sectional area to resist this additional horizontal load. These analyses are described in detail in FHWA-SA-96-071 (1996) and FHWA-SA-96-069 (1996).

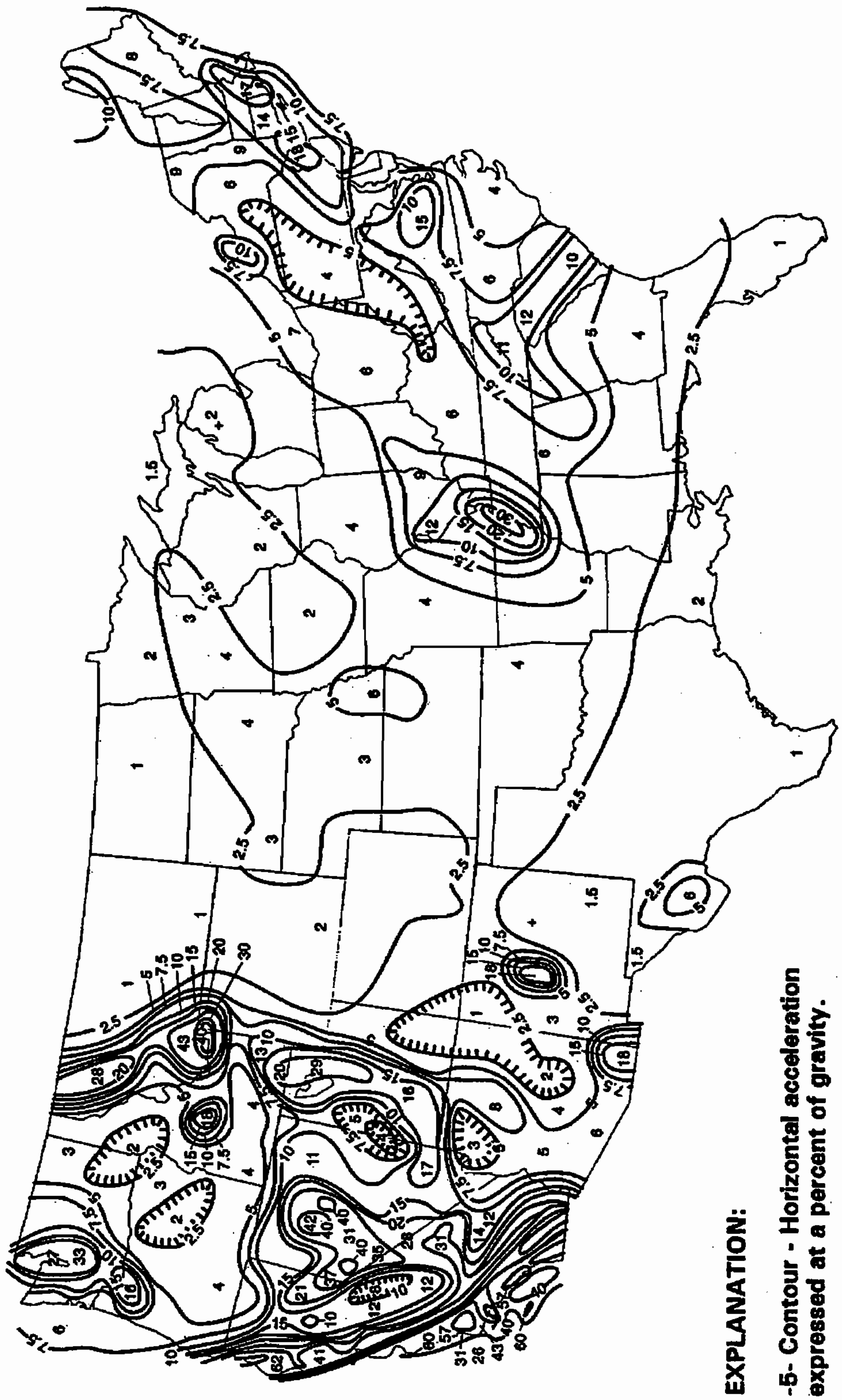


Figure 66. Map of horizontal seismic coefficient (after Algermissen et al., 1982).

The potential for liquefaction should be evaluated when considering the seismic design of a wall system that is to be founded on loose, saturated, cohesionless soil. A liquefaction potential evaluation is typically performed using empirical methods based on past performance data of sand deposits in previous earthquakes. Correlations that employ SPT and CPT results have been developed to evaluate whether a soil may liquefy during the design earthquake (e.g., Seed and Idriss, 1982; Seed and De Alba, 1986). Liquefaction analyses can also be performed using analytical methods based on laboratory evaluation of liquefaction strength and the use of dynamic site response analyses to evaluate the magnitude of earthquake-induced shear stresses.

5.5.5 Wall System Appurtenances

Pre-existing and proposed appurtenances may have a significant effect on design, construction, and cost of a wall system and should therefore be identified during the early stages of project implementation. Examples of appurtenances for wall systems associated with highway applications include: (1) pre-existing and proposed facilities such as underground utilities and drainage systems; (2) traffic barriers and parapet walls; and (3) noise walls.

As part of a site investigation, all pre-existing and proposed facilities that might affect wall system design and construction need to be identified and located. Underground utilities such as telephone cables and gas lines located in close proximity to the proposed wall system alignment may become overly stressed and damaged as a result of vertical and horizontal deformations of the wall system. In such cases, it may be necessary to relocate the utilities or incorporate protective measures during construction, either of which will increase overall construction time and wall system cost. The location of underground utilities will influence the inclination and spacing of anchors and soil nails, and therefore the overall design and sequence of construction. Reinforcing elements for MSE walls and RSS may need to be repositioned, shortened, or bent to permit construction of underground utilities. If underground utilities must be located within the reinforced zone, these wall systems may not be technically feasible or practical to construct.

Earth pressures resulting from dead weight and impact loads from traffic barriers and parapet walls must be accounted for in the design of a wall system. For MSE walls, the upper row of reinforcement is designed to carry additional load resulting from the design impact loads on the traffic barrier or parapet wall.

Noise walls are often incorporated into earth retaining system designs for urban areas. The foundation of a noise wall is designed to resist lateral forces resulting from wind loads. Noise walls are integrally cast to CIP concrete gravity and semi-gravity walls. For MSE, bin, and crib wall systems, the noise wall is typically designed with a foundation which is independent of the wall system. For MSE walls, the columns of the noise wall are founded below the ground surface and spaced so as not to interfere with the reinforcement. For bin and crib systems, a concrete slab may be cast in the upper module to provide support for the base of the noise wall.

5.6 DESIGN REFERENCES

A list of references that contain detailed design and analysis information for the wall systems described in this document are provided in table 8. The documents listed have been prepared by and for public agencies and are generally considered to be representative of the current state-of-practice in earth retaining system design. In addition to those documents listed in table 8, detailed information relating to analysis and design can be found in many soil mechanics and foundation engineering textbooks and handbooks. The reader is also encouraged to become fully familiar with the assumptions, limitations, and content of all references prior to including any particular reference in technical specifications and contract documents.

It should be recognized that design methodologies change for these systems as a result of advances in analysis techniques, advances in construction methods, materials, and equipment, and interpretation of field performance of constructed systems. For this reason, the user should check for any more current guidelines published after the date of this document.

Table 8. Design references for earth retaining systems.

EARTH RETAINING SYSTEM TYPE	*DESIGN REFERENCES*
Rigid Gravity and Semi-Gravity Wall	1. American Association of State Highway and Transportation Officials "*Standard Specifications for Highway Bridges*", Sixteenth Edition, 1994 2. American Society of Civil Engineers "*Retaining and Flood Walls,*" 1994 3. National Cooperative Highway Research Report 343 "*Manuals for the Design of Bridge Foundations,*" 1991 4. NAVFAC DM7.02 "*Foundations and Earth Structures,*" 1986
Prefabricated Modular Gravity Walls	1. American Association of State Highway and Transportation Officials "*Standard Specifications for Highway Bridges*", Sixteenth Edition, 1994 2. NAVFAC DM7.02 "*Foundations and Earth Structures,*" 1986
Mechanically Stabilized Earth (MSE) Walls and Reinforced Soil Slopes	1. American Association of State Highway and Transportation Officials "*Standard Specifications for Highway Bridges*", Sixteenth Edition, 1994 2. FHWA-SA-96-071 "*Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Design and Construction Guidelines,*" 1996 3. FHWA-SA-96-072 "*Corrosion/Degradation of Soil Reinforcement for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes,*" 1996 4. National Cooperative Highway Research Program Report 290 "*Reinforcement of Earth Slopes and Embankments,*" 1987 5. National Concrete Masonry Association "*Design Manual for Segmental Retaining Walls,*" 1993
Non-gravity Cantilevered Walls	1. American Association of State Highway and Transportation Officials "*Standard Specifications for Highway Bridges*", Sixteenth Edition, 1994 2. FHWA-RD-74-57 "*Precast and Cast-in-Place Diaphragm Walls Constructed Using Slurry Trench Techniques,*" 1974 3. FHWA-RD-75-130 "*Lateral Support Systems and Underpinning*", 1976 4. NAVFAC DM7.02 "*Foundations and Earth Structures,*" 1986
Anchored Walls	1. American Association of State Highway and Transportation Officials "*Standard Specifications for Highway Bridges*", Sixteenth Edition, 1994 2. FHWA-RD-74-57 "*Precast and Cast-in-Place Diaphragm Walls Constructed Using Slurry Trench Techniques,*" 1974 3. FHWA-RD-75-130 "*Lateral Support Systems and Underpinning*", 1976 4. FHWA-DP-68-1R "*Permanent Ground Anchors,*" 1988 5. FHWA-RD-81-150 "*Permanent Ground Anchors, Soletanche Design Criteria,*" 1982 6. FHWA-RD-81-151 "*Permanent Ground Anchors, Nicholson Design Criteria,*" 1982 7. FHWA-DP-90-068-003 "*DP-68 Permanent Ground Anchors*, Volume 2, Field Demonstration Project Summaries," 1990 8. FHWA-RD-82-047 "*Tiebacks,*" 1982 9. NAVFAC DM7.02 "*Foundations and Earth Structures,*" 1986
In-Situ Reinforced Walls	1. FHWA International Scanning Tour for Geotechnology Federal Highway Administration "*Soil Nailing Summary Report,*" 1993 2. FHWA-RD-89-193 "*Soil Nailing for Stabilization of Highway Slopes and Excavations,*" 1991 3. FHWA-SA-93-068 "*Soil Nailing Field Inspectors Manual,*" 1994 4. FHWA-SA-96-069 "*Manual for Design and Construction Monitoring of Soil- Nailed Walls,*" 1996 5. National Cooperative Highway Research Program Report 290 "*Reinforcement of Earth Slopes and Embankments,*" 1987 6 FHWA-PA-86-047-84-36 "*Pin-Pile Wall Evaluation,*" 1987 7. FHWA-RD-96-016, FHWA-RD-96-017, FHWA-RD-96-018, and FHWA-RD-96-019 "Drilled and Grouted Micropiles, State-of-Practice Review," 1997

CHAPTER 6

CONTRACTING METHODS AND DOCUMENTS

6.1 INTRODUCTION

The various alternative earth retaining systems described in chapter 1 of this document have seen increasing use on highway construction projects since the early 1980s. The alternative systems have gradually displaced conventional systems through bid alternates, experimental applications, and value engineering proposals. It is estimated that hundreds of millions of dollars have been saved through the use of alternative systems (FHWA, 1988).

Also, as described in chapter 1, an increase in frequency of wall design and construction problems of these alternative systems has accompanied the introduction of these alternative systems. Although the actual causes of each particular problem are unique, the problems have been most commonly attributed to use of alternative wall systems in inappropriate applications; use of inadequate materials or design details; inadequate specifications; lack of specifications enforcement; inequitable bidding procedures; and inconsistent selection, review, and acceptance practices on the part of owner agencies. This chapter addresses issues relating to wall system contracting methods and specifications.

Permanent earth retaining systems are typically contracted using either a method or performance approach. These contracting approaches are defined below.

- *Method Approach*: This type of contracting approach is used for agency or material supplier designs. In the contract documents, wall construction materials, drainage details, and the execution of construction are explicitly specified. This contracting approach is discussed further in section 6.2.

- *Performance Approach*: This type of contracting approach uses approved or generic wall systems or components. Included in the contract documents are lines and grades, as well as specific geometric and design criteria. For this approach, the contractor submits detailed project-specific design calculations and plans for owner review in conjunction with normal working drawing submittals. This contracting approach is discussed further in section 6.3.

Both contracting approaches are valid for most earth retaining systems, if properly implemented. Often, the approach will be selected based on the experience of the owner agency and their engineering consultants with various wall systems, the complexity of the project, the availability of specialty contractors or material suppliers, and the agency philosophy with respect to contracting methods. The advantages and disadvantages of each contracting approach are discussed in subsequent sections of this chapter. In addition to the method and performance approaches, a mixed approach employing both methods can be used. Mixed approaches are not discussed further in this chapter because their appropriateness depends on project-specific conditions.

Regardless of which contracting method is chosen for a specific project, it is highly desirable that each owner agency develop a formal policy with respect to design and contracting of earth retaining systems. The general objectives of such a policy are to:

- obtain agency uniformity in selection of earth retaining system alternatives;
- establish standard policies and procedures for technical review and acceptance of proprietary and generic earth retaining systems;
- establish internal agency responsibility for the acceptance of new earth retaining systems and/or components, and for plan preparation, design review, and construction control;
- develop uniform design and performance criteria standards and construction and material specifications for earth retaining systems; and
- establish guidelines for the selection of method or performance contracting approaches.

6.2 METHOD CONTRACTING APPROACH

6.2.1 Introduction

The method contracting approach includes the development of a detailed set of plans and material and construction specifications for the bidding documents. The advantage of the method approach is that the complete design and specifications are developed and reviewed over an extended design period. This approach enables agency engineers to examine various earth retaining system options during design, but requires an engineering staff trained in all areas of earth retaining system technology.

A disadvantage of the method approach is that for alternate bids, more sets of designs must be developed or reviewed. Therefore, agency resources must be expended even though only one wall system will be constructed. Another disadvantage is that agency personnel may be unfamiliar with newer and potentially more cost-effective systems and may not consider them during the design stage. Similarly, wall systems whose construction is based on proprietary equipment and methods may be unfamiliar to agency personnel and will therefore not be considered.

The method contracting approach is best suited to fill walls where the available technology is either traditional or widely disseminated and reasonably well-established. Knowledgeable contractors and material suppliers of fill wall systems are widespread throughout the United States. Complete detailed plans based on the agency's geometric requirements and design criteria are often furnished, at no expense, by proprietary material suppliers, especially those involved in MSE wall systems.

For cut wall applications, the method contracting approach is generally appropriate for the more widely used and well developed wall systems such as non-gravity cantilevered sheet-pile walls, anchored walls, and soil-nailed walls. The method contracting approach may also be suitable for cut wall systems with which the agency has developed significant experience in design and construction.

6.2.2 Required Elements for Method Specifications

Plan and elevation sheets (drawings) prepared using the method approach should typically include at least the following items:

- plan views showing the horizontal alignment and offset from the horizontal control line to the face of the wall, the beginning and end stations for wall construction, and all appurtenances that affect construction of the wall;
- elevation views indicating the elevation at the top and bottom of the wall, the beginning and end stations for wall construction, horizontal and vertical positions at points along the wall, whole station points, and locations and elevations of the final ground line;
- cross sections showing limits of construction, backfill requirements, excavation limits, as well as mean high water level, design high water level, and drawdown conditions, if applicable;
- any general notes required for design and construction;
- all construction constraints such as staged construction, vertical clearance, right-of-way limits, construction easements, etc.;
- typical sections;
- dimensional and alignment tolerances during construction;
- required construction procedures;
- foundation preparation requirements (for fill walls);
- external and internal drainage requirements and details;
- all details for connections to traffic barriers, copings, parapets, noise walls, and attached lighting; and
- payment limits and quantities.

In addition, the following items are required for specific wall types:

Rigid Gravity and Semi-Gravity Walls

- footing size and location and, for cantilever and counterfort walls, the location of all footing reinforcing steel;
- location and details for deep foundations, if required;
- location of construction and expansion joints and applicable details; and
- typical sections of the wall showing all concrete dimensions and, for cantilever and counterfort walls, the position of all reinforcing steel;

Prefabricated Modular Gravity Walls

- length, size, and type of module, and positions for which module lengths change; and
- footing size and location;

MSE Walls and Reinforced Soil Slopes

- length, size, and type of soil reinforcement, and positions for which reinforcement length, size, and/or type changes;
- facing panel layout and the type of panel, the elevation of the top of the levelling pad and footings, and the distance along the face of the wall to all steps in the footings and/or levelling pads;
- alignment and elevation of internal drainage systems, and method of passing reinforcing elements around the drainage systems;
- details for facing panels and for erosion control for RSS showing all dimensions necessary for construction, and the location of all reinforcement attachment devices;
- details for architectural treatment or surface finish of the facing panels;
- details for construction around drainage facilities, overhead sign footings, or other structures; and
- corrosion protection requirements for reinforcing elements;

Non-Gravity Cantilevered Walls

- size, location, and minimum embedment depth of all vertical structural elements;
- for soldier pile and lagging construction, size of temporary lagging and all details for final facing and final facing connections to soldier piles; and
- details for facing treatment or permanent facing installation;

Anchored Walls

- size, location, and minimum embedment depth of all vertical structural elements;
- for soldier pile and lagging construction, size of temporary lagging and all details for final facing and final facing connections to soldier piles and/or walers;
- location of all anchors and structural connection details for the anchor head to the soldier pile or waler system;
- corrosion protection requirements or details for the anchor head, the unbonded length, and the anchor length;
- required anchor capacity, inclination, minimum unbonded length, and anchor bond length for each anchor;
- required lock-off load;
- requirements or details for methods and frequency of proof and performance testing of anchors; and
- details for facing treatment or permanent facing installation;

Soil Nailed Walls

- nail spacing, length, inclination, and size of nail;
- minimum drill hole diameter for each nail and required nail capacity;
- corrosion protection requirements or details for the nail;
- minimum thickness of temporary and/or permanent facing with details for reinforcement and size of nail cover plates;

- requirements or details for methods and frequency of testing nail capacity; and

- details for facing treatment or permanent facing installation.

6.3 PERFORMANCE CONTRACTING APPROACH

6.3.1 Introduction

For the performance contracting approach (often referred to as "line and grade" or "two line drawing" approach), the agency prepares drawings showing the geometric requirements of the wall system, material specifications for the wall system or components that may be used, and wall performance requirements. The wall systems or components that are permitted for use are either: (1) specified by the agency; or (2) they are on a pre-approved list maintained by the agency.

The performance approach (also referred to as the end result approach) offers several benefits when used with appropriate specifications and prequalification of suppliers, specialty contractors, and materials. Design of the structure is the responsibility of the contractor and is usually performed by a trained and experienced contractor, wall supplier, or engineering consultant. Prequalified material components have been successfully and routinely used together; this may not be the case for in-house design with generic specifications for components. This enables engineering costs and manpower requirements for an agency to be decreased, and transfers some of the design cost to construction.

The disadvantage of the performance approach is that agency engineers may not be experienced with the wall technology and, therefore, may not be fully qualified to review and approve the wall design and any construction modifications. Newer and potentially more cost-effective systems may be rejected by the agency due to the lack of confidence of agency personnel to review and approve these systems.

With the performance contracting approach, bid quantities are obtained from specified pay limits denoted on the "line and grade" drawings and can be bid on a lump sum or unit price basis. The technical basis for detailed designs to be submitted after contract award are contained as complete special provisions or by reference to AASHTO or agency manuals. Performance criteria, which usually include permissible horizontal/vertical deformations at completion of construction and/or maintenance of ground-water levels, must be defined and made part of the contract documents.

Three principal methods have been used to implement the performance approach. These methods are described below.

- *Method 1*: Detailed wall designs are developed by preselected contractors based on line and grade information approved by owner agency personnel. These designs are then included in the bid documents. A non-proprietary design is often included as the base alternative.

- *Method 2*: "Schematic" or conceptual plans are developed by preselected specialty contractors/suppliers based on geometries and performance requirements specified by the owner agency. The plans are reviewed and approved by the owner agency. These plans are then included in the bid documents.

- *Method 3*: Complete performance based specifications, including geometric requirements, design criteria, geotechnical parameters, and short and long-term wall performance criteria are included in the bid documents.

The first method has been successfully and widely used for the construction of certain fill wall systems (e.g., MSE walls and bin walls). In these cases, prefabricated construction materials are supplied by national specialty suppliers, and the wall system is erected by the general contractor or a subcontractor of his choice using the proprietary construction method, if chosen.

The advantage of the second method is that specialty contractors/suppliers are more likely to submit their solutions for concept review and inclusion in the bid documents than for Method 1. This is because Method 2 plans require only limited preparation effort, and development of a detailed design is only necessary if they are the successful bidder. This results in a more competitive bidding process. The disadvantage of this method is that total project requirements are less well-defined and may lead to misunderstandings and claims. With this method, pay quantities are developed by the agency for each conceptual plan so that the bids for different plans can be compared. Alternatively, bids are based on a lump sum for each structure. General contractors have often objected to the use of this method, particularly for certain cut wall applications (e.g., anchored walls, soil-nailed walls, micropile walls) since public agencies have required general contractors to bond the work at a fixed price and to use the agency-selected subcontractor to perform part of the work. The objection can sometimes be removed by adding agency plans for a traditional solution to the retention problem that can be constructed by a general contractor. This procedure further provides a framework to evaluate the potential savings of alternative designs.

The third method is very advantageous for situations in which the agency has a well-defined understanding of the performance requirements for the wall system, but where the agency may be unclear on the most applicable technology to achieve those requirements. The disadvantage of this method is that the agency must carefully develop the complete performance requirements, methods for field checking and control, and a reasonable cost estimate without knowledge of the technology to be used.

For any type of performance specification, different wall designs may have unique pay quantities reflecting the materials and methods required, or it may be bid as a lump sum with unit prices for added or deleted items based on changed conditions. A lump sum payment for the completed wall system is often used as the pay quantity since actual quantities of materials may be wall-system dependent.

6.3.2 Required Elements for Performance Specifications

Regardless of which of the three performance-based methods is used, the agency must prepare and include as part of the contract documents, the information listed below:

Geometric Data

- plan views showing the horizontal alignment and offset from the horizontal control line to the face of the wall, the beginning and end stations for the wall construction, and all appurtenances that affect construction of the wall;

- elevation views indicating the elevation at the top and bottom of the wall, the beginning and end stations for the wall construction, horizontal and vertical positions at points along the wall, whole station points, and locations and elevations of the final ground line;

- cross sections showing limits of construction, backfill requirements, excavation limits, as well as mean high water level, design high water level, and drawdown conditions, if applicable;

- all construction constraints such as staged construction, vertical clearance, right-of-way limits, construction easements, etc.;

- location of utilities, signs, etc., and any loads that may be imposed by these appurtenances; and

- data obtained as part of a subsurface investigation and geotechnical testing program.

Design Requirements

- reference to specific governing sections of an agency design manual (materials, structural, hydraulic, and geotechnical), construction specifications, and special provisions; if none is available, reference to current AASHTO Standard Specifications (AASHTO, 1994), both Division I - Design and Division II - Construction, may be used;

- magnitude, location, and direction of external loads due to bridges, overhead signs and lights, and traffic surcharges;

- limits and requirements of drainage features beneath, behind, above, or through the structure;

- geotechnical design parameters such as friction angle, cohesion, and unit weight, as well as electrochemical properties of the soils to be utilized; and

- size and architectural treatment of permanent facing for the wall or slope erosion protection requirements, if applicable;

Performance Requirements

- design life for the structure and, if applicable, required corrosion protection;

- tolerable horizontal and vertical movements of the structure and methods of measuring these movements; and

- permissible range of variation in ground-water levels and methods of ground-water level measurement.

6.3.3 Review and Approval

Where a performance contracting approach is used, the review process may be made prior to or after the bid, depending on which of the three methods is used. The evaluation by agency structural and geotechnical engineers must be rigorous and consider as a minimum the following items:

- conformance to the project line and grade;

- conformance of the design calculations to the special provisions or agency standards or codes such as the current AASHTO Standard Specifications (AASHTO, 1994) with respect to design methods;

- corrosion protection details, where required;

- development of design details at obstructions such as drainage structures or other appurtenances;

- external and internal drainage features and details;

- architectural treatment of the wall face or slope erosion protection methods, if applicable;

- monitoring methods as required by the performance specifications; and

- field testing program details for evaluating the capacity of anchors, soil nails, etc., as required.

CHAPTER 7

INSPECTION AND MONITORING

7.1 INTRODUCTION

The purpose of this chapter is to provide guidance regarding inspection and monitoring of earth retaining systems. Inspection refers to activities carried out during construction to verify that the wall system is constructed in accordance with project plans and specifications. Inspection is the primary component of plan and specifications enforcement. Monitoring refers to measurements of wall performance that are not required by the project specifications and that are generally carried out after construction is complete. The type of contracting approach used for the wall (i.e., method or performance) affects the scope of inspection and monitoring activities and determines which party (i.e., owner agency, contractor, or a combination of both) will carry them out.

Inspection activities, if properly conducted, play a vital role in the production of a high quality wall system because conformance to project plans and specifications should result in a wall system that will perform adequately for the intended design life. Inspection may involve evaluation of the following: (1) conformance of wall components and soils to material specifications; (2) conformance of construction methods to execution specifications; and (3) conformance to short-term performance specifications, if any. Inspection activities can be carried out by either the owner agency, the contractor, or a combination of both as described in the following paragraph.

For a wall system contracted using the method approach, inspection activities are typically carried out by the owner agency. The specific inspection activities are described in the method specification and the results of the activities form the basis for acceptance of construction. For a wall system contracted using the performance approach, many of the inspection activities are carried out by the contractor under his own volition. The owner agency will typically carry out only a limited number of inspection activities as appropriate to verify the material and performance requirements of the performance specification. The results of the limited inspection activities form the basis for acceptance of construction.

Monitoring activities typically involve measurement of long-term performance of the wall system. Monitoring is most often performed for critical wall systems or systems that employ new construction methods or materials. Monitoring activities are carried out almost exclusively by the owner agency, often to obtain local performance data on new wall systems. As monitoring activities are not required by the project specifications, monitoring results are not used to form decisions for wall construction acceptance. For the same reason, monitoring activities are not affected by contracting method, although monitoring may often be motivated by performance requirements in a performance specification (e.g., measurement of wall deformations).

The remainder of this chapter is organized as described below.

- Inspection, as it relates to enforcement of material specifications, is described in section 7.2. Issues concerning conventional construction materials are discussed briefly. Issues concerning specialized materials used for earth retaining system construction are discussed in greater detail.

- Inspection, as it relates to enforcement of execution and short-term performance specifications, is described in section 7.3. The section begins with discussion of conventional issues concerning construction lines and grades. Issues concerning construction methods are then discussed for specific fill and cut wall systems. The section also includes discussion of issues concerning measurement of short-term performance.

- Monitoring is briefly discussed in section 7.4. The section includes a description of information that may be obtained from post-construction monitoring.

7.2 INSPECTION OF CONSTRUCTION MATERIALS

7.2.1 Introduction

Contract specifications for earth retaining systems include a description of the acceptable materials to be used for construction. Specifications describe minimum requirements for materials such as steel, concrete, and geosynthetics, as well as prefabricated components such as bin or crib modules, segmental facing panels and connection devices for MSE walls, and permanent facing elements for cut wall systems. These minimum requirements may be defined explicitly by the owner agency or reference to standard specifications such as AASHTO or ASTM may be incorporated into the contract specifications. The purpose of this section is to describe inspection activities that are conducted to verify compliance with material specifications. Conventional materials and more specialized construction materials are discussed separately.

For both conventional and specialized construction materials, the determination of material conformance to contract specifications can be made in several ways including: (1) conformance testing of the materials at the construction site using field tests; (2) reviewing material certifications provided by the fabricator at the construction site; (3) verifying that pre-qualified material and wall components are used; and (4) verifying that prefabricated elements are of the appropriate dimensions and are undamaged.

7.2.2 Conventional Materials

Conventional construction materials include steel, concrete, and soil. Material requirements for these materials are well-established and defined in the AASHTO and ASTM specifications. Steel components for wall construction typically include reinforcing bars, steel beams, and sheet-piles.

Standard requirements for these steel components include minimum yield strength and required shape and dimensions. For concrete, minimum compressive strengths are prescribed in the contract documents. Standard specifications for soil materials include gradation, minimum friction angle, and electrochemical requirements for wall backfill soils, and compaction requirements for both foundation and backfill soils.

7.2.3 Specialized Materials

The purpose of this section is provide information on issues involved in inspection of several specialized wall materials. Specialized materials are those that are used for wall construction but are not commonly encountered in highway construction. Agency personnel performing inspection of these materials may therefore be unfamiliar with appropriate inspection activities. In addition, as detailed material specifications for these materials may not be available in standard reference documents, differences may exist between specifications for different projects. Such differences further complicate the inspection process.

Discussion of significant inspection issues for a number of specialized materials is given below.

Geosynthetic reinforcement for MSE walls and RSS

Inspection should include examination of: (1) documentation of manufacturing quality control procedures including quality control certificates; (2) handling methods to assess whether physical or ultraviolet damage has occurred since manufacture; (3) documentation of laboratory testing of tensile and creep characteristics of material, load-carrying seams, and geosynthetic-soil interfaces; and (4) results of on-site conformance testing.

Erosion control material for RSS

Inspection should include examination of: (1) documentation of manufacturing quality control procedures; and (2) documentation of laboratory testing of physical properties, tensile characteristics, and ultraviolet radiation resistance.

Bentonite slurry for slurry (diaphragm) walls

Inspection should include examination of: (1) documentation of bentonite source and quality; (2) records indicating age of slurry (i.e., time for bentonite hydration); and (3) results of on-site tests for slurry viscosity, specific gravity, and sand content.

Cement slurry for soil mixed walls

Inspection should include examination of: (1) documentation of cement source and quality; (2) records of cement mixing quantities; and (3) results of on-site tests for compressive strength of partially cured soil-cement samples.

Cement grout for anchor, soil nail and micropile installation

Inspection should include examination of: (1) documentation of cement source and quality; (2) records indicating water/cement ratio and quantity of any grout admixtures; (3) authorization for use of any grout admixtures; and (4) documentation of chemical and physical suitability of mix water.

Corrosion protection materials for anchors, soil nails, and micropiles

Inspection should include examination of: (1) documentation of laboratory testing for physical and chemical properties of anti-corrosion grease (e.g., flash point, chloride content); (2) documentation of source and quality of protection sleeves (usually polyethylene or polypropylene); (3) continuity of epoxy coating applied to steel components; and (4) continuity of grout fill in annular space between anchors, soil nail, or micropile and encapsulating sleeve.

Shotcrete facing for soil-nailed walls

Inspection should include examination of: (1) documentation of cement source and quality; (2) records indicating water/cement ratio and quantity of any shotcrete admixtures (e.g., plasticizers, accelerators); (3) results of laboratory tests for compressive strength; and (4) documentation of chemical and physical suitability of mix water.

7.3 INSPECTION OF CONSTRUCTION ACTIVITIES

7.3.1 Introduction

Inspection of construction activities is performed to verify that the execution of construction is consistent with that described in the contract documents. In this section, information on inspection of construction is presented for specific fill and cut wall systems. Inspection activities generally applicable to all wall systems are also discussed. Construction errors common to these systems are also addressed. This information is intended to provide guidance for owner agency personnel on issues and activities that should be considered as part of the inspection process.

7.3.2 Lines and Grades

Inspection for all earth retaining systems includes field verification that the wall is being constructed in accordance with the geometric requirements described in the contract specifications. The following items are typically considered when inspecting for line and grade requirements:

- appropriate depth of wall embedment is achieved;
- vertical and horizontal position of all drainage outlets is correct;
- wall face batter is within appropriate tolerances over the entire height of the wall;
- wall foundation level is correct;

- wall and any necessary excavation are being constructed within the available ROW; and
- horizontal alignment, elevations of the top and bottom of wall, and wall termination points are as shown on the construction drawings.

7.3.3 Construction Methods

The purpose of this section is to provide information on issues involved in the inspection of fill and cut wall construction. Issues that may not be covered in a typical contract specification or those that tend to be critical to quality construction are emphasized. Common construction errors are also mentioned.

7.3.3.1 Fill Walls

Prefabricated Modular Gravity Walls

Inspection of bin and crib wall construction may emphasize compaction of the soils within each bin or crib module. These modules are relatively small and the compaction of the backfill requires small, hand-operated equipment. This type of compaction is relatively time consuming and labor intensive as compared to the compaction operations for other fill walls. An additional issue is that bearing strips and/or padding may be required between successive levels of modules. These elements must be installed prior to placing successive levels of modules.

Mechanically Stabilized Earth (MSE) Walls

Inspection activities for a MSE wall include: (1) checking all tolerances and alignments as the wall is being constructed; and (2) monitoring compaction and the placement of reinforcement. For vertical walls with precast panels, the panels should be slightly battered so that any compaction-induced movements of the wall will not be apparent in the profile of the final wall face. The construction of walls with geotextile or geogrid facings requires special forms. These forms enable the backfill to be compacted against the flexible wrapped face of the wall without causing distortion of the wall face.

Proper compaction operations for MSE walls are critical to the appearance and performance of the wall. Lightweight compaction equipment should be used immediately behind the wall and compaction should start from the back of the wall and progress towards the retained soil. All compaction equipment should have a smooth compaction surface to avoid damaging reinforcing elements.

Inspection for the placement of reinforcement for MSE walls should include: (1) verifying that the connection between the wall facing and the reinforcement is made properly; (2) ensuring that the geosynthetic reinforcement is pulled tight towards the retained soil prior to dumping backfill;

(3) monitoring placement of reinforcement in and around appurtenances such as internal drainage systems.

Reinforced Soil Slopes (RSS)

Many of the inspection activities performed for RSS are similar to those performed for MSE walls. These include checking all tolerances and monitoring the placement of reinforcement and soil backfill compaction. Specific inspection activities for RSS include: (1) checking that secondary reinforcement is constructed to contract specifications including appropriate vertical spacing and reinforcement length; and (2) monitoring the placement of temporary or permanent erosion control material or other facing elements. Construction monitoring of erosion control material should include verifying that anchor trenches are constructed in accordance with the construction drawings and that the length and location of anchorage devices such as pins are also as shown on the construction drawings.

7.3.3.2 Cut Walls

Sheet-pile Walls

The construction of a sheet-pile wall requires the use of pile-driving equipment. Pile-driving equipment can induce significant ground vibrations and it is recommended that a survey of the condition of any nearby structures be undertaken.

The performance of a steel sheet-pile wall is influenced by the quality of the ball and socket interlock between adjacent sheet-piles. Steel sheet-piles are typically driven in pairs and so it is important that the sheet-pile with the ball end be driven first. If the sheet-pile with the socket end is driven first, it may clog with soil and make it difficult to drive the adjacent pile. Regular inspection of the sheet-pile tops should also be performed to assess damage resulting from driving through relatively hard soils. This may also be an indication that the pile-driving hammer and/or cushion is inappropriate for the soil conditions.

Soldier Pile and Lagging Walls

Driven soldier piles should be inspected to assess damage at the pile tops. If precast concrete lagging is employed, deviations of the soldier piles from vertical may make it difficult to place the concrete lagging. Also, lagging must be placed at an appropriate time after excavation to ensure that local soil failure does not occur. Excavation to place the lagging should be done carefully to minimize the gap that exists between the lagging and the excavated soil face.

Slurry (Diaphragm) Walls

Slurry (diaphragm) wall construction requires relatively detailed construction inspection due to the use of specialized equipment and materials. These walls are usually constructed by specialty contractors and, as such, there are no currently accepted industry construction and material specifications for these systems. Several key construction inspection issues are described herein.

The construction of a wall panel for a slurry (diaphragm) wall is performed in a narrow trench. For this reason, construction tolerances related to panel width, depth of wall, and alignment of the wall are critical. Proper construction of the guidewalls is essential to ensure that accurate alignment is maintained. Guidewalls should be cast against compact subgrade.

On-site quality control of the slurry and concrete is also necessary. During placement of concrete, plots of concrete volume placed versus the rise of the concrete within the excavated trench should be recorded. This information can be used to evaluate whether a cave-in has occurred.

After the wall has been exposed due to excavation, the wall should be checked to verify that excessive seepage is not occurring through vertical panel joints or through any openings in the wall face.

Tangent Pile/Secant Pile Walls

Construction inspection for tangent pile walls and secant pile walls is similar to that for drilled shafts. Inspection includes verifying that drilling techniques that are consistent with the soil type and ground-water conditions are being used and that all construction tolerances are maintained. For tangent pile walls it is important that vertical tolerances are maintained if a relatively watertight wall is required.

Soil Mixed Walls

Soil mixed walls employ specialized equipment, materials, and methods. For this reason, industry-accepted construction and material specifications are not yet available. Inspection personnel should monitor the following mixing and positioning parameters during construction of a soil mixed wall:

- shaft rotation during penetration and withdrawal;
- velocity of shaft withdrawal;
- cement content of soil-cement mixture;
- pumping rate of soil-cement slurry mixture; and
- amount of overlap between adjacent piles.

Anchored Walls

For anchored walls, the spacing, inclination, method of drilling, drill hole size, and length of each anchor must be consistent with the design assumptions. Inspection personnel must pay close attention to these issues because the tieback anchors are the principal load-carrying components of the wall system. Significant deviations in any of these items should be reported to the design engineer.

Construction inspection during installation of the anchors in the drill hole includes: (1) checking that centralizers are in place at appropriate locations along the anchor; (2) monitoring the anchor insertion operation for indications that the drill hole has collapsed; and (3) assessing damage to any anchors just prior to insertion. Construction inspection during grouting of a anchor should include verifying that grout injection pressures and grout volumes are consistent with design assumptions.

The major component of construction inspection activities for anchored walls is monitoring proof and performance testing. These test procedures have been previously described in section 3.3.3.5. Construction inspection should include evaluating the results of proof and performance tests against acceptance criteria outlined in the contract specifications. Prior to testing, an assessment of the loading devices to be used for the proof and performance tests should be made. This assessment includes checking the calibration certifications for all jacks, gauges, and load cells. In addition, all deformation gauges should be checked to verify that the movements generated in the anchor during testing will be accurately measured.

Soil-Nailed Walls

Construction inspection for soil-nailed walls includes verifying that: (1) admissible excavation depths are not exceeded; (2) drill holes have not collapsed; (3) nail pullout testing meets specifications; and (4) contract-specified procedures for structural shotcrete application are followed. The excavated soil material should be examined during construction and any differences in soil type between the excavated soil and that assumed for design should be reported to the design engineer so that necessary construction and/or design changes can be made.

Micropile Walls

Construction inspection activities for the installation of micropiles are similar to that for the installation of anchors. It is particularly important that inspection personnel verify that the appropriate length micropiles are used. If the purpose of the micropile wall is to stabilize an active landslide, horizontal measurement devices may be required. Inspection should then include verifying that measurements are made accurately and on a regular basis and that steps are taken to minimize the potential for damaging the measuring devices.

7.3.4 Performance Requirements

Contract specifications may require that certain performance criteria be satisfied during construction. These performance criteria may include: (1) maintaining a dewatered site; (2) limiting horizontal movement of the wall face and/or settlement of adjacent structures; and (3) maintaining ground-water levels in the backfill and/or retained soil to within an acceptable range of variation. If these items are part of a performance specification, methods to monitor these items during construction will typically be included in the contract documents. Inspection personnel should also be alert to construction operations that may create locally unstable conditions which may be detrimental to wall system performance. An example of such an operation is the stockpiling of materials on the edge of an open excavation. Any such operations should be brought immediately to the attention of those with the authority to halt operations.

7.4 POST-CONSTRUCTION MONITORING

7.4.1 Introduction

Monitoring typically involves measurements of long-term wall performance that are carried out after construction is complete. Such measurements are not generally required by the project specifications but are conducted by the owner agency in order to monitor wall performance (e.g., wall displacements) and/or to gain insight into overall wall system behavior (e.g., loads in wall components). Monitoring activities conducted primarily to monitor wall performance are categorized as limited monitoring, while monitoring activities conducted primarily to gain insight into wall behavior are categorized as comprehensive monitoring. Limited monitoring and comprehensive monitoring are discussed in the following subsections.

Both levels of monitoring are performed using a variety of measurement devices, or instrumentation. Instrumentation is selected based on its ability to measure the desired response and to survive the expected project climate and environment. Selection of appropriate instrumentation should also consider the range of response magnitudes that are anticipated relative to the range and sensitivity of the candidate instruments. In addition, the required degree of automation for the instrumentation depends largely on the anticipated time intervals between data collection. It is noted that instrumentation to measure basic climate information at the project site (i.e., temperature and rainfall) is sometimes included if temperature extremes and storm events are expected to affect wall performance.

7.4.2 Limited Monitoring

Limited monitoring of earth retaining systems will typically consist of measurement of horizontal movements of the wall facing, ground-water elevations in the backfill and retained soil, and/or settlement of any adjacent structures. Such measurements would be recorded at a small number of locations along the wall. Typical instrumentation used to record such measurements is described below.

Horizontal movements of wall facing

This response may be assessed using visual observations of the magnitude of wall tilt. More detailed measurements are performed through level and horizontal surveying of permanent survey markers installed on the wall face. Photogrammetric surveying techniques have also been used for these measurements.

Ground-water elevations behind wall

This response is most often measured using open standpipe piezometers installed in the backfill and/or retained soil behind the wall.

Settlements of adjacent structures

This response is most often measured using level surveying of permanent survey markers installed on the adjacent structure. Such markers are installed in close proximity to the structure foundation.

7.4.3 Comprehensive Monitoring

Comprehensive monitoring of earth retaining systems will typically consist of measurement of both internal and external responses of the structure. External responses include items such as those mentioned above for a limited monitoring program (e.g., horizontal movements of the wall facing). For comprehensive monitoring, however, such external measurements would likely be recorded at a greater number of locations along the structure. Internal responses include items such as horizontal and vertical movements within the structure, horizontal and vertical stresses within the structure, and strains within wall system components. Typical instrumentation used for internal response measurements is described below.

Internal movements

This response is most often measured using horizontal and vertical inclinometers. Extensometers can also be used to measure horizontal movements. Vertical movements can also be measured with surveyed settlement plates or liquid level gauges.

Internal stresses

This response can be measured using earth pressure cells. The installed orientation of the cell determines the plane for pressure measurement. In some cases, horizontal stresses on the wall facing are measured indirectly for MSE walls and anchored walls by measuring tensile loads in the soil reinforcements or anchors at points adjacent to the wall facing.

Strains within wall system components

This response is measured using strain or displacement gauges that are affixed to the wall component during construction. Strain gauges include resistance-types and vibrating wire-types. Displacement gauges include induction coil-types and wire telltales. Measurements of strain can be used to estimate stresses through an established stress-strain relationship.

REFERENCES

1. Achilleos, E., "User Guide for PCSTABL 5M," Joint Informational Report JHRP-88/19, Indiana Department of Highways and Purdue University School of Civil Engineering, West Lafayette, Indiana, 1988.

2. Algermissen, S.T., D.M. Perkins, P.C. Thenhaus, S.L. Hanson, and B.L. Bender, "Probabilistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States," United States Geological Survey, Open-File Report 82-1033, 1982.

3. American Association of State Highway and Transportation Officials (AASHTO), "Standard Specifications for Highway Bridges," Sixteenth Edition, 1994.

4. AASHTO, "Manual on Subsurface Investigations," 1988.

5. American Association of State Highway and Transportation Officials-Associated General Contractors of America-American Road and Transportation Builders Association (AASHTO-AGC-ARTBA) Joint Committee, Subcommittee on New Highway Materials, Task Force 27 Report, "In-Situ Soil Improvement Techniques," August 1990.

6. American Society of Civil Engineers (ASCE), Draft Report, "Guidelines for Braced and Tied-back Excavations," Geotechnical Engineering Division, Committee on Earth Retaining Structures, 1994a.

7. ASCE, "Retaining and Flood Walls, "Technical Engineering and Design Guides as Adapted from the U.S. Army Corps of Engineers, No. 4, 1994b.

8. American Society for Testing and Materials (ASTM), "Slurry Walls: Design, Construction, and Quality Control," ASTM STP 1129, 1992.

9. ASTM, "Annual Book of ASTM Standards, Section 4, Construction," 1994.

10. Anderson, T.C., "Earth Retention Systems, Temporary and Permanent," Meeting Preprint, Proceedings of the 32nd Annual Soil Mechanics and Foundation Engineering Conference Proceedings, Minneapolis, 1984.

11. Barker, R.M., J.M. Duncan, K.B. Rojiani, P.S.K. Ooi, C.K. Tan, and S.G. Kim, "Manuals for the Design of Bridge Foundations," National Cooperative Highway Research Program Report 343, Transportation Research Board, 1991.

12. Bowles, J.E., "Foundation Analysis and Design," McGraw-Hill Publishing Company, 1982.

13. Briaud, J., "The Pressuremeter Test for Highway Applications," Federal Highway Administration, Report FHWA-IP-89-008, July 1989.

14. Bruce, D.A., "Two New Specialty Geotechnical Processes for Slope Stabilization," Stability and Performance of Slopes and Embankments - II, American Society of Civil Engineers, Geotechnical Specialty Publication No. 31, pp. 1505-1519, 1992.

15. Bruce, D.A. and I. Juran, "Drilled and Grouted Micropiles, State-of-Practice Review," 4 volumes, Federal Highway Administration, Reports FHWA-RD-96-016, FHWA-RD-96-017, FHWA-RD-96-018, and FHWA-RD-96-019, 1997.

16. Byrne, R.J., R.G. Chassie, J.W. Keeley, D.A. Bruce, P. Nicholson, J.L. Walkinshaw, A. Dimillio, K.A. Jackura, R. Chapman, and C. Ludwig, "FHWA International Scanning Tour for Geotechnology," Soil Nailing Summary Report, Federal Highway Administration, Report FHWA-PL-93-020, June 1993.

17. Cheney, R.S., "Permanent Ground Anchors," Federal Highway Administration, Report FHWA-DP-68-1R, March 1988.

18. Cheney, R.S., "Selection of Earth Retaining Structures: The Owner's Perspective," Design and Performance of Earth Retaining Structures, American Society of Civil Engineers, Geotechnical Special Publication No. 25, pp. 52-66, 1990.

19. Cheney, R.S., "DP-68 Permanent Ground Anchors, Vol. 2, Field Demonstration Project Summaries," Federal Highway Administration, Report FHWA-DP-90-068-003, April 1990.

20. Cheney, R.S. and R.G. Chassie, "Soils and Foundations Workshop Manual," Federal Highway Administration, Report FHWA-HI-88-009, July 1993.

21. Clough, G.W., and T.D. O'Rourke, "Construction Induced Movements of Insitu Walls," Design and Performance of Earth Retaining Structures, American Society of Civil Engineers, Geotechnical Special Publication No. 25, pp. 439-470, 1990.

22. D'Appolonia, D.J., E. D'Appolonia and D. Namy, "Precast and Cast-In-Place Diaphragm Walls Constructed Using Slurry Trench Techniques," Proceedings of Workshop on Cut-and-Cover Tunneling, Federal Highway Administration, Report FHWA-RD-74-57, January 1974.

23. Dash, U., "Pin-Pile Wall Evaluation," Federal Highway Administration and Pennsylvania Department of Transportation, Report FHWA-PA-86-047-84-36, March 1987.

24. Duncan, J.M., G.W. Clough, and R.M. Ebeling, "Behavior and Design of Gravity Earth Retaining Structures," Design and Performance of Earth Retaining Structures, American Society of Civil Engineers, Geotechnical Special Publication No. 25, pp. 251-277, 1990.

25. Elias, V., "Durability/Corrosion of Soil Reinforced Structures," Federal Highway Administration, Report FHWA-RD-89-186, December 1990.

26. Elias, V., "Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes," Federal Highway Administration, FHWA-SA-96-072, 1996.

27. Elias, V, and B.R. Christopher, "Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Design and Construction Guidelines," Federal Highway Administration, FHWA-SA-96-071, 1996.

28. Elias, V., and I. Juran, "Soil Nailing for Stabilization of Highway Slopes and Excavations," Federal Highway Administration, Report FHWA-RD-89-193, June 1991.

29. Elms, D.A., and G.R. Martin, "Factors Involved in the Seismic Design of Bridge Abutements," Proceedings, Workshop on Seismic Problems Related to Bridges, Applied Technology Council, Berkeley, 1979.

30. Federal Highway Administration, "Geotechnical Engineering Notebook, Geotechnical Guideline No. 2, Earth Retaining Structures - Review and Acceptance Procedures," June 1988.

31. "Foundation Engineering Handbook, Second Edition," H.Y. Fang, ed., Chapman and Hall, New York, 1991.

32. Goldberg, D.T., W.E. Jaworski, and M.D. Gordon, "Lateral Support Systems and Underpinning, Construction Methods," Federal Highway Administration, FHWA-RD-75-130, April 1976.

33. Golder Associates, Inc., "Manual for Design and Construction Monitoring of Soil Nailed Walls," Federal Highway Administration, FHWA-SA-96-069, 1996.

34. Lambe, P.C. and L.A. Hansen, eds., "Design and Performance of Earth Retaining Structures," American Society of Civil Engineers, Geotechnical Special Publication No. 25, 1990.

35. Lizzi, F., "Reticulated Root Piles to Correct Landslides," Meeting Preprint 3370, American Society of Civil Engineers, ASCE Convention and Exposition, Chicago, 1978.

36. Mitchell, J.K. and W.C.B. Villet, "Reinforcement of Earth Slopes and Embankments," National Cooperative Highway Research Program Report 290, Transportation Research Board, June 1987.

37. Mononobe, N., "Earthquake-Proof Construction of Masonry Dams," Proceedings, World Engineering Conference, Volume 9, 1929.

38. Naval Facilities Engineering Command (NAVFAC) DM7.02, "Foundations and Earth Structures," Department of the Navy, Alexandria, Virginia, 1986.

39. Nicholson, P.J., D.D. Uranowshi, and P.T. Wycliffe-Jones, "Permanent Ground Anchors, Nicholson Design Criteria," Federal Highway Administration, Report FHWA-RD-81-151, September 1982.

40. Okabe, S., "General Theory of Earth Pressure," Journal of Japanese Society of Civil Engineers, Volume 12, No. 1, 1926.

41. O'Rourke, T.D., and C.J.F.P. Jones, "Overview of Earth Retention Systems: 1970-1990, "Design and Performance of Earth Retaining Structures," American Society of Civil Engineers, Geotechnical Special Publication No. 25, pp. 22-51, 1990.

42. Pearlman, S.L., B.D. Campbell, and J.L. Withiam, "Slope Stabilization Using In-Situ Earth Reinforcements," Stability and Performance of Slopes and Embankments - II, American Society of Civil Engineers, Geotechnical Specialty Publication No. 31, pp. 1333-1348, 1992.

43. Pearlman, S.L., and D.E. Himick, "Anchored Excavation Support Using SMW (Soil Mixed Wall)," Deep Foundations Institute, 18th Annual Member's Conference and Meeting, Pittsburgh, October 1993.

44. Pfister, P., G. Evers, M. Guillaud, and R. Davidson, "Permanent Ground Anchors, Soletanche Design Criteria," Federal Highway Administration, Report FHWA-RD-81-150, September 1982.

45. Porterfield, J.A., D.M. Cotton, and R.J. Byrne, "Soil Nailing Field Inspectors Manual," Federal Highway Administration, Report FHWA-SA-93-068, April 1994.

46. Post-Tensioning Institute (PTI), "Recommendations for Prestressed Rock and Soil Anchors," 1995.

47. Riaund, J., and J. Miran, "The Cone Penetrometer Test," Federal Highway Administration, Report FHWA-SA-91-043, February 1992.

48. Riaund, J., and J. Miran, "The Flat Dilatometer Test," Federal Highway Administration, Report FHWA-SA-91-044, February 1992.

49. Richardson, E.V., "Evaluating Scour at Bridges," Federal Highway Administration, Report FHWA-IP-90-017, November 1995.

50. Schmertmann, G.R., R. Bonaparte, V.E. Chouery-Curtis, and R.D. Johnson, "Design Charts for Geogrid-Reinforced Soil Slopes," Proceedings of Geosynthetics 1987, New Orleans, pp. 108-120, 1987.

51. Seed, H.B., and P. De Alba, "Use of SPT and CPT Tests for Evaluating the Liquefaction Resistance of Sands," Use of In-Situ Tests in Geotechnical Engineering, American Society of Civil Engineers, Geotechnical Special Publication No. 6, pp.281-302, 1986.

52. Seed, H.B., and I.M. Idriss, "Ground Motions and Soil Liquefaction During Earthquakes, Monograph No. 5," Earthquake Engineering Research Institute, Berkeley, California, 1982.

53. Sharma, S., "XSTABL, An Integrated Slope Stability Analysis Program for Personal Computers," Interactive Software Designs, Inc., Moscow, Idaho, 1994.

54. Simac, M.R., R.J. Bathurst, R.R. Berg, and S.E. Lothspeich, "Design Manual for Segmental Retaining Walls (Modular Concrete Block Retaining Wall Systems)," National Concrete Masonry Association, Herndon, Virginia, 1993.

55. Terzaghi, K., and R.B. Peck, "Soil Mechanics in Engineering Practice," John Wiley and Sons, Inc., New York, 1967.

56. Weatherby, D.E., "Tiebacks," Federal Highway Administration, Report FHWA-RD-82-047, July 1982.

57. Wright, S., "UTEXAS3 - A Computer Program for Slope Stability Calculations," User's Manual, Shinoak Software, Austin, Texas, 1995.

58. Zornberg, J., and J.K. Mitchell, "Poorly Draining Backfills for Reinforced Soil Structures-A State of the Art Review," Geotechnical Engineering Report No. UCB/GT/92-10, University of California, Berkeley, 1992.

HTA-20/3-97(2M)EW