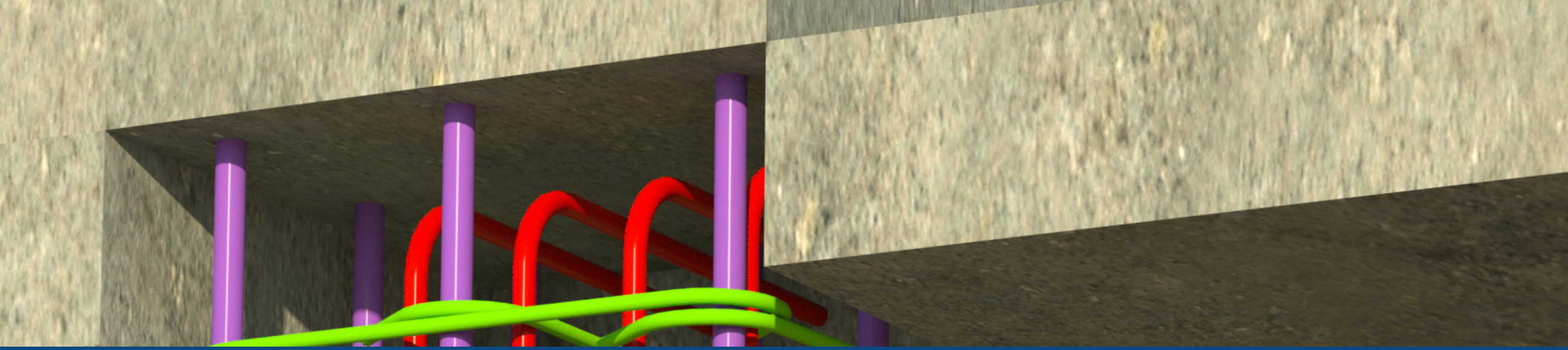
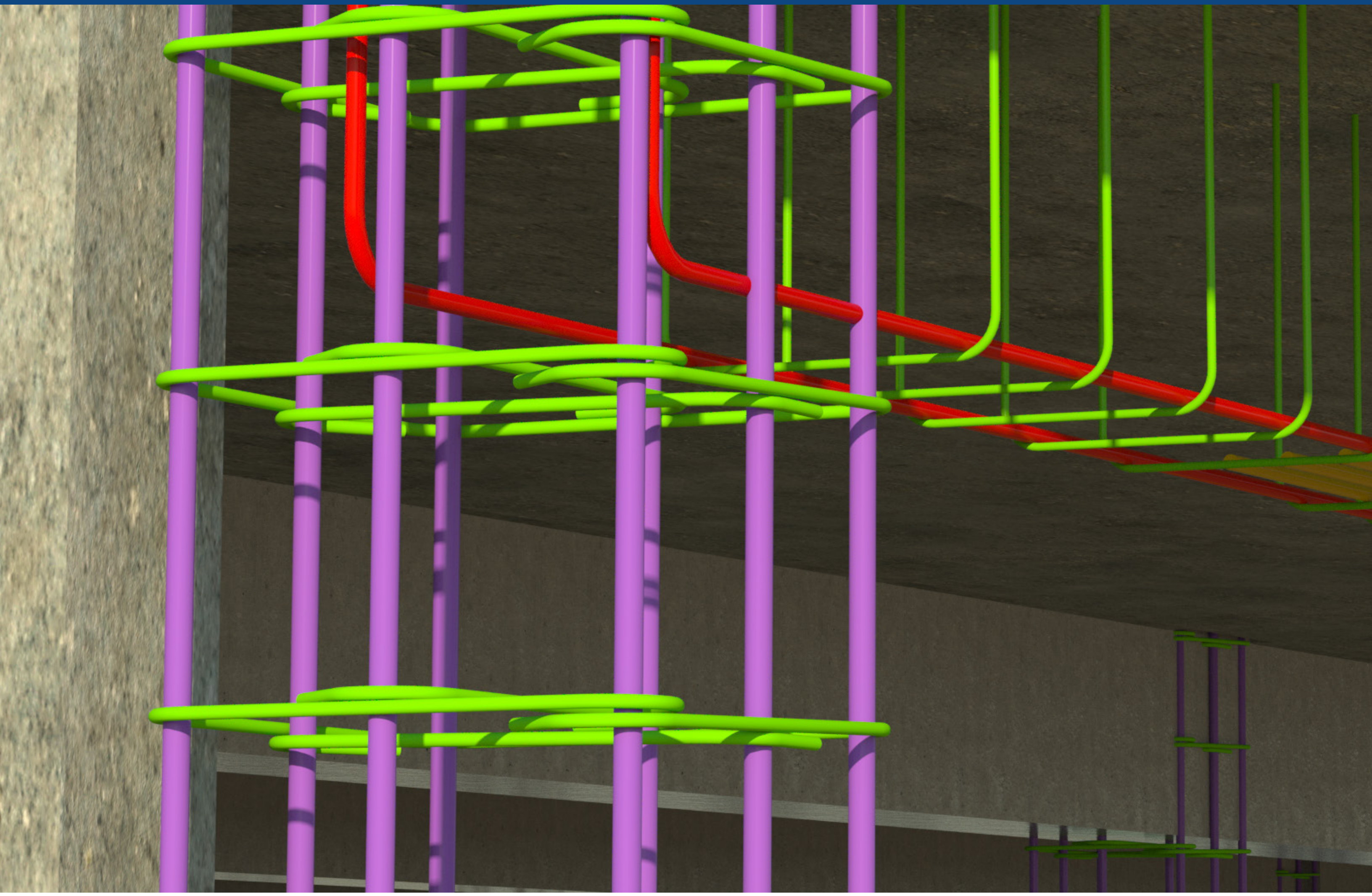


An ACI Manual

# ACI Reinforced Concrete Design Handbook

## A Companion to ACI 318-19



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# ACI REINFORCED CONCRETE DESIGN HANDBOOK

## A Companion to ACI 318-19

ACI MNL-17(21)
Volume 2

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# ACI REINFORCED CONCRETE DESIGN HANDBOOK
## Volume 1 ~ Tenth Edition



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# DEDICATION

This edition of *The ACI Reinforced Concrete Design Handbook*, MNL-17(21), is dedicated to the memory of Daniel W. Falconer and his many contributions to the concrete industry. He was Managing Director of Engineering for the American Concrete Institute from 1998 until his death in July 2015.

Dan was instrumental in the reorganization of “Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)” as he served as ACI staff liaison to ACI Committee 318, Structural Concrete Building Code; and ACI Subcommittee 318-SC, Steering Committee. His vision was to simplify the use of the Code for practitioners and to illustrate the benefits of the reorganization with MNL-17. His oversight and review comments were instrumental in the development of the ninth edition of the Handbook.

An ACI member since 1982, Dan served on ACI Committees 344, Circular Prestressed Concrete Structures, and 373, Circular Concrete Structures Prestressed with Circumferential Tendons. He was also a member of the American Society of Civil Engineers. Prior to joining ACI, Dan held several engineering and marketing positions with VSL Corp. Before that, he was Project Engineer for Skidmore, Owings, and Merrill in Washington, DC. He received his BS in civil engineering from the University at Buffalo, Buffalo, NY and his MS in civil and structural engineering from Lehigh University, Bethlehem, PA. He was a licensed professional engineer in several states.

In his personal life, Dan was an avid golfer, enjoying outings with his three brothers whenever possible. He was also an active member of Our Savior Lutheran Church in Hartland, MI, and a dedicated supporter and follower of the Michigan State Spartans basketball and football programs. Above all, Dan was known as a devoted family man dedicated to his wife of 33 years, Barbara; his children Mark, Elizabeth, Kathryn, and Jonathan; and two grandsons, Samuel and Jacob.

In his memory, the ACI Foundation has established an educational memorial. For more information visit http://www.scholarshipcouncil.org/Student-Awards. Dan will be sorely missed for many years to come.

# FOREWORD

*The ACI Reinforced Concrete Design Handbook* provides assistance to professionals engaged in the design of reinforced concrete buildings and related structures. This edition is a major revision that brings it up-to-date with the approach and provisions of "Building Code Requirements for Structural Concrete" (ACI 318-19).

*The ACI Reinforced Concrete Design Handbook* provides dozens of design examples of various reinforced concrete members, such as one- and two-way slabs, beams, columns, walls, diaphragms, footings, and retaining walls. For consistency, many of the numerical examples are based on a fictitious seven-story reinforced concrete building. There are also many additional design examples not related to the design of the members in the seven-story building that illustrate various ACI 318-19 requirements.

Each example starts with a problem statement, then provides a design solution in a three-column format—Code provision reference, short discussion, and design calculations—followed by a drawing of reinforcing details, and finally a conclusion elaborating on a certain condition or comparing results of similar problem solutions.

In addition to examples, almost all chapters in *The ACI Reinforced Concrete Design Handbook* contain a general discussion of the related ACI 318-19 chapter.

This edition of *The ACI Reinforced Concrete Design Handbook* was updated and enhanced by ACI staff engineers under the auspices of the ACI Technical Activities Committee (TAC). Each chapter was reviewed by at least two reviewers, who provided valuable comments, suggestions, and insights. The following reviewers are gratefully acknowledged and thanked:

| | | | |
|---|---|---|---|
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Special thanks are due to a number of outside contributors to this Manual. Dirk Bondy and Kenneth Bondy provided software used to analyze and design the post-tensioned beam example, in addition to their valuable comments and suggestions. StructurePoint and Computers and Structures, Inc. (SAP 2000 and Etabs) provided use of their software to perform analyses of structure and members. The Bridge Software Institute (BSI) provided use of their software and their expertise in the development of the design examples on deep foundations.

*The ACI Reinforced Concrete Design Handbook* is published in two volumes: Chapters 1 through 11 are published in Volume 1 and Chapters 12 through 15 are published in Volume 2. Design aids and a moment interaction diagram Excel spreadsheet are available for free download from the following ACI webpage links:
https://www.concrete.org/MNL1721Download1
https://www.concrete.org/MNL1721Download2

**Keywords:** anchoring to concrete; beams; columns; cracking; deflection; diaphragm; durability; flexural strength; footings; frames; piles; pile caps; post-tensioning; punching shear; retaining wall; shear strength; seismic; slabs; splicing; stiffness; structural analysis; structural systems; strut-and-tie; walls.

Trey Hamilton
*Managing Editor*

# VOLUME 2: CONTENTS

# CHAPTER 12—RETAINING WALLS

## 12.1—General

Retaining walls provide horizontal resistance to a soil mass and prevent it from assuming its natural slope. Isolated retaining walls are used to provide a significant and localized change in grade elevation as may be required for building, roadway, or bridge sitework.

Retaining walls can be classified based generally on the method of attaining stability against the lateral load imposed by the retained earth. Gravity retaining walls (Fig. 12.1a(a)) use their own weight and that of the retained soil for stability and are either lightly reinforced or contain no reinforcement. Cantilever retaining walls (Fig. 12.1a(b)) are a reinforced concrete arrangement of cantilever wall and footing such that the wall resists the lateral soil force and the weight of the soil on the heel of the footing provides the primary contribution to overall stability. There are several variants of cantilever retaining walls including walls with either heel only (Fig. 12.1a(c)) or toe only (Fig. 12.1a(d)) that can be used when a typical footing will encroach on a property line.

Cantilever retaining walls are generally economical up to a height of approximately 20 ft. Beyond 20 ft, buttresses or counterforts can be used to tie the stem and footing together and to improve their strength and stiffness (Fig. 12.1b). They can also be used for conditions where backfill pressures are unusually high. Counterforts provide an advantage visually, as they create an unobstructed stem face on the visible side of stem.

Basement walls are another classification of retaining wall; they are used in commercial or residential structures to provide useable space below the surrounding grade of the building structure (Fig. 12.1c). Basement walls may also serve simultaneously as bearing walls or shear walls, or both.

This chapter of the Manual covers primarily cantilever retaining walls (Examples 2 through 6) that are covered

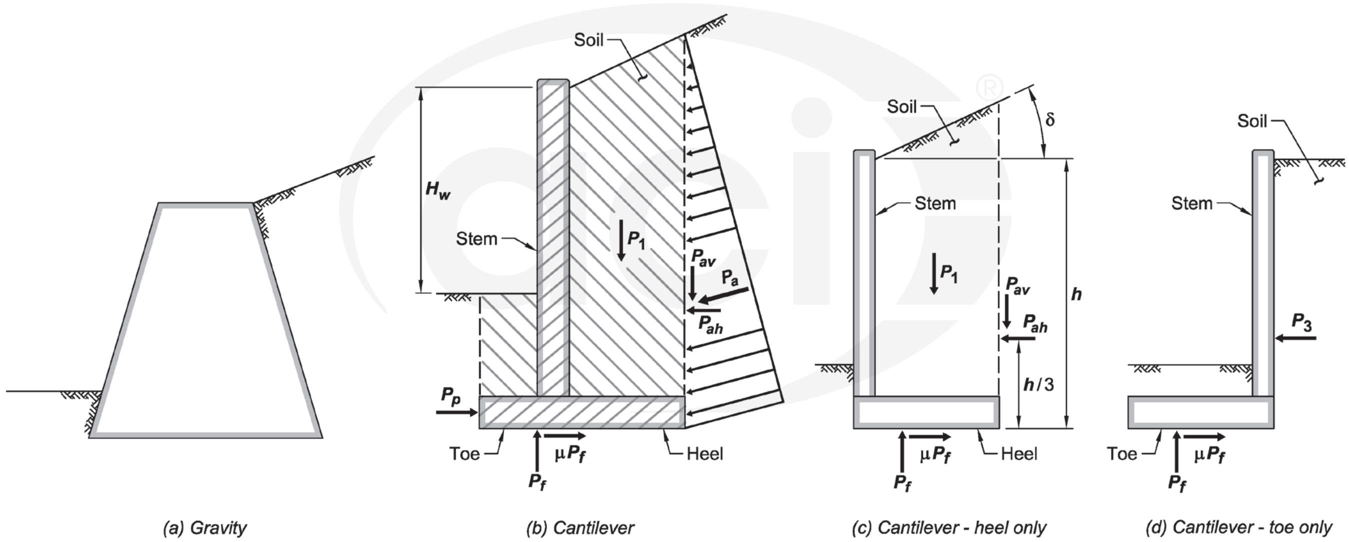


*Fig. 12.1a—Retaining wall classifications.*

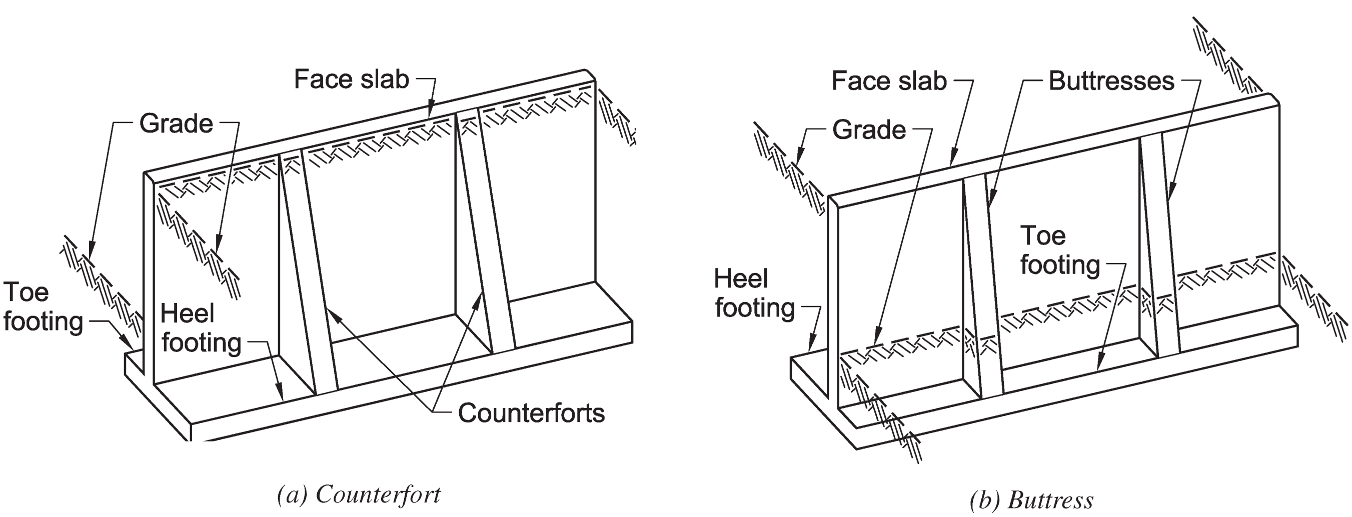


*Fig. 12.1b—Cantilever retaining wall classifications.*

in Code Chapter 13—Foundations. In addition, Example 1 provides a design example of a basement wall that also serves as a bearing wall and shear wall. Because the basement wall resists axial load and in-plane shear, its design is covered in Code Chapter 11—Walls. The design approach for out-of-plane load effects from soil pressure, however, is similar to that of cantilever retaining walls.

## 12.2—Retaining wall stability

A cantilever retaining wall is an assembly of a vertical stem and a horizontal footing; the footing is typically considered in two parts: heel and toe. The stem provides horizontal resistance to the overturning force of the soil through the moment connection to the footing at the base of the stem. The moment transferred from the stem to the footing is resisted by the upward soil pressure under the toe and the downward soil weight on the top of the heel; the overturning failure mode associated with this behavior is illustrated in Fig. 12.2a(a). The failure is caused by a combination of rigid body rotation of the assembly and the loss of soil bearing resistance under the toe.

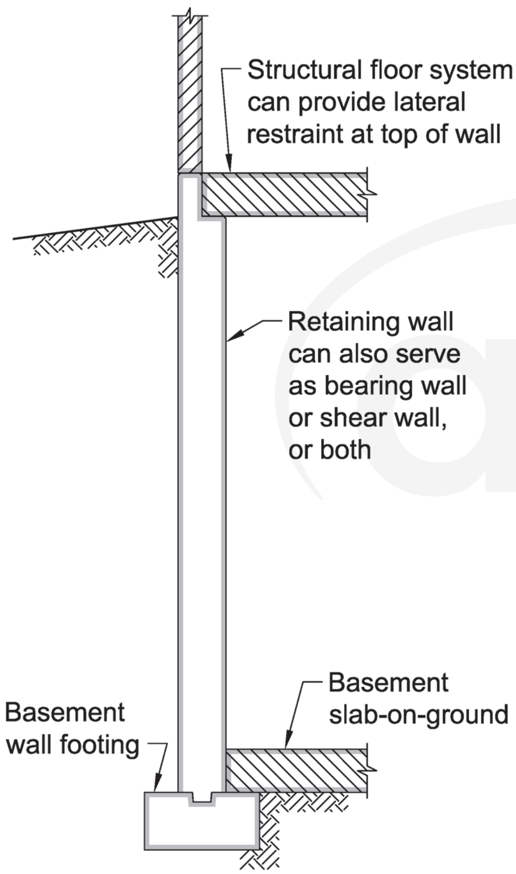


*Fig. 12.1c—Basement wall.*

The stem also transfers the lateral soil force into the footing through shear at the connection. In turn, the lateral movement of the footing is resisted by the frictional force between the footing base and soil as well as the passive pressure in front of the footing toe. The failure mode associated with this behavior is illustrated in Fig. 12.2a(b).

In situations where the factor of safety against sliding failure is low, and there are site constraints against lengthening the heel, a "key" can be constructed below the footing to increase sliding resistance, as shown in Fig. 12.2b.

Bearing failure under the footing can also occur if the soil underlying the footing has been improperly prepared or if it is stratified with poor material. Excessive settlement or rotation or both can result from these conditions (Fig. 12.2a(c)).

This chapter is focused on the structural analysis and design of cantilever retaining wall and basement wall. As part of the examples in this chapter, calculations are conducted to check the stability of the retaining walls against failure due to sliding, overturning, or bearing. The following factors of safety (FS) against these soil-related failures were used in the calculations at the end of this chapter:

(a) FS $\geq$ 1.5: against sliding failure
(b) FS $\geq$ 2.0: against overturning failure
(c) FS $\geq$ 3.0: against bearing failure

These factors among other geotechnical parameters are usually provided by the geotechnical engineer and are not within the scope of this Manual.

## 12.3—Retaining wall structural design

The reinforced concrete stem and footing flexure and shear design strengths must be at least equal to the factored moments and shears determined from the wall analysis using the forces and reactions shown in Fig. 12.2(b). Figure 12.3b depicts the deflected shape under load of the stem, heel, toe, and key and related tension areas (shown by cracks).

In situations where the factor of safety against sliding failure is low, and there are site constraints against lengthening the heel, a "key" can be constructed below the footing to increase sliding resistance, as shown in Fig. 12.3b.

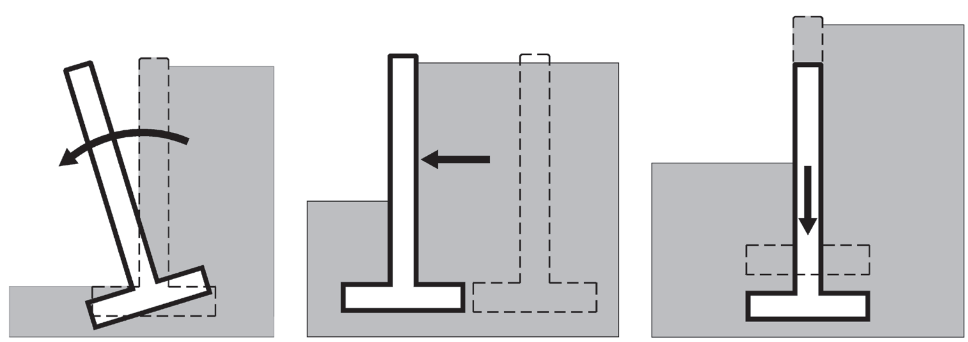


*Fig. 12.2a—Cantilever wall soil failure modes.*

## 12.4—Design limits

Cantilever retaining wall design is covered in Code Chapter 11—Foundations, which addresses both cantilever retaining walls and counterfort or buttressed cantilever retaining walls. The wall stem is addressed in Code Section 13.3.6 and the footing is considered a one-way shallow foundation similar to a strip footing for a bearing wall; footing design is addressed in Code Section 13.3.2, One-way shallow foundations.

**12.4.1** *Wall stem*—According to Code Section 13.3.6.1, retaining wall stems are designed as one-way slabs in accordance with the applicable provisions of Code Chapter 7. Design of the stem is typically done by considering a unit length of wall as is done for one-way slab design. The wall thickness is sometimes tapered to provide material savings as the moment and shear demand decrease nearer the top of the cantilever. A tapered front face, however, complicates the formwork construction and reinforcement layout. Consequently, oftentimes the wall thickness is kept constant on stems of lower height. The minimum recommended stem thickness is 8 in., but many engineers prefer a 10 in. minimum.

For preliminary calculations, choose a stem thickness at the base between 7 and 12 percent of the retained earth height *h*, as shown in Fig. 12.4.1a. Stem thickness is verified by satisfying shear design strength and moment design strength requirements. Code Section 13.3.6.3 indicates that for walls of uniform thickness, the critical section for flexure and shear should be taken at the interface between the stem and footing. For walls with varying thickness, shear and moment should be investigated throughout the height of the stem.

Axial loads, including the wall stem weight and frictional forces of the backfill acting on the wall stem, should be considered in the stem design in addition to bending due to eccentric vertical loads, surcharge loads, and lateral earth pressure (Fig. 12.4.1b).

A small axial load tends to increase the moment strength of the wall according to the interaction equation, so ignoring the axial load is conservative.

**12.4.2** *Buttresses and counterforts*—According to Code Section 13.3.6.2, the stem of a counterfort or buttressed cantilever retaining wall should be designed as a two-way slab using the applicable provisions of Chapter 8. Buttresses or counterforts are analyzed and designed as rectangular beams. Horizontal reinforcement connects the stem to buttresses or counterforts, and vertical reinforcement connects the footing to the buttresses or counterforts. If stirrups are used to provide shear strength, they should be detailed in accordance with ACI 318. If straight bars are used, their yield strength should be fully developed through straight embedment or hooks at the interface of the stem or footing and the buttress or counterfort.

The stem and buttress or counterfort are designed as cantilever beams, fixed at the footing, with a tributary load area equal to the distance between individual buttresses or counterforts.

**12.4.3** *Wall footings*—According to Code Section 13.3.2.1, wall footings for cantilever retaining walls should be designed as one-way shallow foundations using the applicable provisions of Chapter 7 and Chapter 9. For preliminary calculations, the footing length can be estimated as 40 to 70

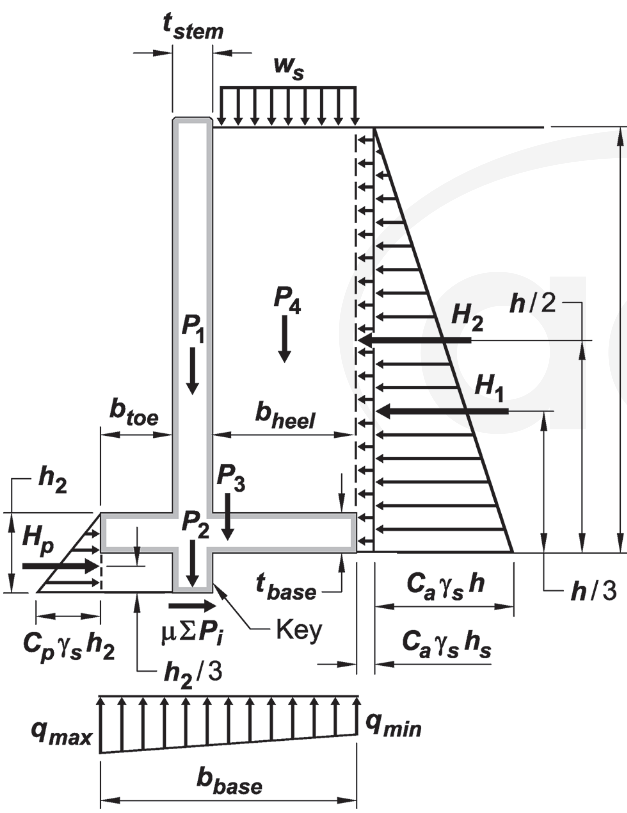


*Fig. 12.3a—Cantilever retaining wall free-body diagram.*

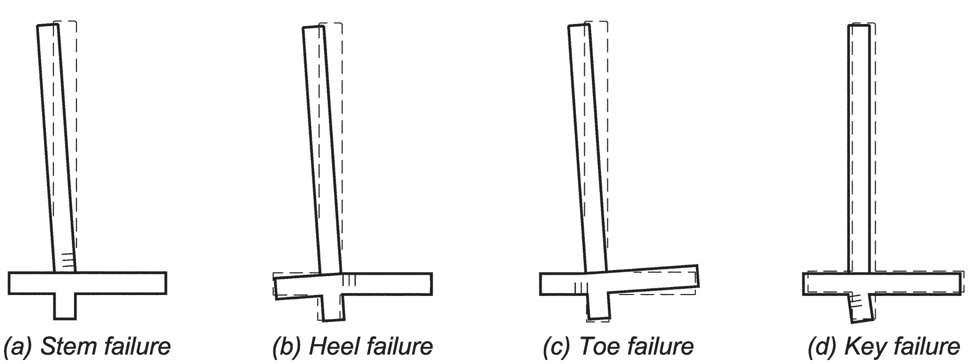


*Fig. 12.3b—Cantilever wall failure modes and deflected shapes.*