AN EXPERT SYSTEM FOR THE PRELIMINARY DESIGN OF CANTILEVER RETAINING WALLS

BY

NASRULLAH ABEER

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Civil and Environmental Engineering

1991

ABSTRACT

AN EXPERT SYSTEM FOR THE PRELIMINARY DESIGN OF CANTILEVER RETAINING WALLS

BY

NASRULLAH ABEER

An application of knowledge-based expert systems (KBES) in the domain of geotechnical engineering design was developed and evaluated. The KBES, named TWALL, performs the preliminary design of cantilever retaining walls, including the proportioning of wall dimensions to ensure external stability (i.e., wall stability against overturning, sliding and bearing failures) and provision of sufficient steel to ensure internal stability of the wall. TWALL is structured to design for either external stability only or both external stability and internal stability.

In TWALL, a hierarchical decomposition of the task of wall design is used as a basis for system organization. The knowledge base of TWALL is developed in production rule language provided by the LEVEL5 expert system shell. There are a total of 297 rules used in the knowledge base. The developed system is semi-automated with a user-friendly interface and contains proportioning algorithms developed to obtain a

design with only few trials.

The design of a cantilever retaining wall is influenced by a large number of parameters including wall height, engineering properties of foundation soil and backfill material, and water levels. A parametric sensitivity analysis was performed to assess the effect of these parameters on the wall design. The wall design is also influenced by the assumed lateral earth pressure conditions (at-rest or active) behind the wall. The effect of earth pressure assumptions on wall dimensions and overall cost has also been studied for different wall heights and other parameters.

At the present state of geotechnical knowledge, it is difficult to relate parameters affecting wall design in a purely algorithmic way to the proportioning of the wall. Engineering judgement and experience is required for the selection of required design parameters. Some heuristics are written to help novice designers in the selection of soil parameters and wall dimensions.

To my parents, wife Sumera and
children Umar, Aisha and Hamzah

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and appreciation to my thesis advisor Dr. Thomas F. Wolff for his guidance and encouragement during the course of this research. Appreciation is also expressed to Dr. Orlando Andersland, Dr. Perviz Soroushian and Dr. Grahame J. Larson for their moral support and helpful suggestions as members of my guidance committee.

I wish to express my sincere thanks and appreciation to Dr. Wayne Bergstrom and Messrs; Mark Alvey, Scott Gleason, Kevin Miller and his colleagues and Ralph Strom for their help in knowledge elicitation. I also thank the students of Michigan State's CE 818, CE 419 and CE 499 courses for their participation in the validation of TWALL.

Finally, I am indebted to the Pakistan Army, Corps of Engineers for providing financial support without which it would have been impossible to complete this study.

TABLE OF CONTENTS

CHAPTER 4. TWALL: KNOWLEDGE BASE

CHAPTER 5. PARAMETRIC SENSITIVITY ANALYSIS

CHAPTER 6. EFFECT OF EARTH PRESSURE ASSUMPTIONS ON WALL DESIGN

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Cantilever Retaining Walls

A retaining wall is a structure that provides lateral resistance necessary to prevent horizontal movement of a retained soil mass (Newman 1976). There are several types of retaining walls that can perform this function including gravity walls, cantilever walls and crib walls. The wall type (considered under study) here is the cantilever retaining wall.

The terms associated with a cantilever retaining wall cross section are shown in Figure 1.1. The stem acts as a cantilever beam which must resist lateral pressure caused by the backfill material. The base is the structural component that must transmit vertical forces and to some extent, horizontal forces, to the foundation soil. The heel is the portion of the base on the back side of the wall and the toe is the base portion on the front side of the wall. A base key may be provided to increase lateral resistance in case the foundation soil is weak. The key can be at different locations along the base. The backfill is material placed to

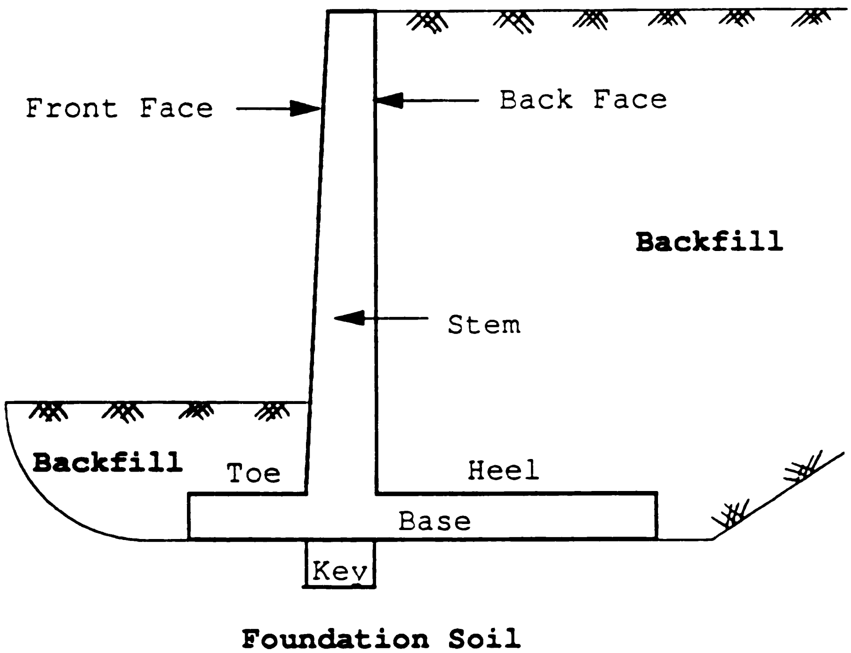


Figure 1.1 Parts of cantilever retaining wall

elevate the ground surface to the design elevation.

1.2 Problem Statement

Cantilever retaining walls are designed by trial and error. Trial section dimensions are assumed and earth pressures acting on that section are computed based on some earth pressure theory. The stability of the wall is checked against overturning, sliding and bearing capacity failures and against excessive settlements. The section dimensions are revised until the wall is externally stable against these failure modes with a reasonable safety margin and reasonable economy. Then computations for bending moments, shears and required reinforcement are performed to ensure internal stability of the wall.

For the safe and economical design of a cantilever retaining wall, a geotechnical engineer is required to make use of his experience and judgment besides using theoretical and empirical methods. The design process also involves certain heuristics (rules of thumb) that can only be applied efficiently by an engineer experienced in wall design.

This study critically assessed heuristic rules required to implement the design of a cantilever retaining wall. Indeed it was found and will be shown that the design task may require consideration of hundreds of "rules".

Manual computational methods available for the design of cantilever retaining walls are tedious and time consuming and can be viewed as things of past in this age of computers. Conventional computer programs such as TWDA (Price et al., 1980) and B-24 (Bowles 1988) are being used for the design of retaining structures. But it is difficult for a novice user to understand their workings and there are problems associated with altering such programs to suit new requirements.

The algorithmic nature of traditional conventional programming languages such as BASIC and FORTRAN limits information representation to numerical and graphical means. Design problems such as cantilever wall design require professional expertise, knowledge and experience for decision making, rather than simply an analysis of numerical problems. Thus, there is some advantage developing design tools that can handle rules and experience than that provided by the algorithmic solutions.

Researchers in the area of artificial intelligence, (a branch of computer science) have recently invented techniques to create programs that are more interactive, knowledge intensive, user-friendly and easily modifiable than earlier FORTRAN (or BASIC) computer programs (e.g., CBEAR and TWDA). These programs are called knowledge-based expert systems (KBES) or expert systems (ES).

KBES are essentially attempts to model the performance of human experts within their respective domains (Fenves et al., 1984). Knowledge in KBES is more explicit, accessible and expandable than the knowledge embedded in the codes of a conventional program. KBES uses a systematic approach for finding the answer to the problem and explaining its behavior through an explanation facility (Rychener 1988).

Over the past few years, a number of KBES have been developed for some selected problems in civil engineering. Some of the areas in which the KBES are developed include structural design (Maher 1988), interpretation and geotechnical characterization of data from cone penetrometers (Mullarkey 1985), management and architectural design (Flemming 1988), selection and preliminary design of earth retaining structures (Hutchinson et al., 1987) and rehabilitation of earth retaining walls (Adams et al., 1990).

The few developed KBES related to retaining structures are limited either to selection of the appropriate type of wall for a given situation or to use for diagnostic purposes only. No published literature was found where an attempt has been made to use an expert system technology for the structural design of cantilever retaining walls by combining heuristics with analytical methods being used for the design.

1.3 Objectives of the Study

1.3.1 Main Objectives

The two primary objectives of this study were to develop a semi-automated knowledge-based expert system for the preliminary design of cantilever retaining walls and to assess the suitability of such an approach to this class of problems.

1.3.2 Sub-Efforts

Supporting the main objective are several sub-efforts which are summarized in the following sections.

1.3.2.1 Literature Review

This effort consisted of reviewing previous research on earth pressure, current design procedures for cantilever retaining walls and capabilities of knowledge-based expert systems for the development of present system.

1.3.2.2 Knowledge Elicitation

This effort involved heuristic knowledge elicitation from engineers experienced in the design of retaining structures. Knowledge elicited from such experts was mostly used to verify the heuristics developed from parametric sensitivity analysis. This effort is described in Chapter 7.

1.3.2.3 Parametric Sensitivity Analysis

The stability of a cantilever wall is affected by a number of variables including wall height, base and heel length, backfill and foundation soil parameters, wall friction, backfill slope and water table. By understanding clearly how these variables (independently and in combination) affect wall stability, one can better proportion the wall dimensions for safe and economical design with fewer trials. This analysis also helped to develop heuristics to guide novice program users.

An example of sensitivity analysis would be the effect of toe length. A change in toe length effects the distribution of upward soil pressure under the base. With a short toe, the upward soil pressure may exceed the downward pressure at the intersection of heel and stem and the point of maximum shear and moment shifts from the intersection point toward the free end of the heel. In this situation, a common assumption used for the structural design of heel (i.e., the point of maximum shear and moment is at the intersection of heel and stem) is violated. A parametric sensitivity analysis can help to determine a minimum toe length so that this assumption is not violated. This analysis is described in Chapter 5.

1.3.2.4 Active Versus At-Rest Analysis

The assumption regarding state of stress in the backfill for computing lateral earth pressure behind cantilever retaining walls is somewhat controversial. Many references (e.g., Das 1984, Bowles 1988) recommend assuming an active state of stress in the backfill for earth pressure predictions. On the other hand, recently some agencies (e.g., the U.S. Army Corps of Engineers, 1989) have recommended designing for at-rest conditions. These assumptions affect the magnitude of lateral earth pressure which ultimately affect wall dimensions and overall cost of the wall.

A design tool such as TWALL provides a convenient way to study the quantitative effect of active and at-rest assumptions on required quantity of materials and cost of the wall. This analysis also helped in writing some heuristic rules. Chapter 6 describes this analysis.

1.3.2.5 Synthesis of Knowledge - New Recommendations for Design

The development of TWALL necessitated a critical look at a variety of design recommendations and required generating numerous designs for the developments of heuristics. It is useful after this experience to reflect on findings and make one's own recommendations regarding prediction of earth pressure behind cantilever retaining walls and proportioning of wall dimensions. Chapter 8 summarizes this effort.

CHAPTER 2

CURRENT PRACTICE IN CANTILEVER RETAINING WALL DESIGN

2.1 General

The general approach to the design of a cantilever retaining wall is to analyze conditions that would exist at the time of impending collapse and to apply suitable factors of safety to prevent such a collapse. This approach is known as limit design and requires limiting equilibrium mechanics (Lambe and Whitman 1969). The design must ensure external and internal stability of the wall. External stability refers to wall stability against overturning, sliding and bearing capacity failures. The wall is considered internally stable when all its parts have sufficient flexural and shear strength to resist applied bending moments and shears.

2.2 Wall Proportions

Site conditions impose certain constraints on wall proportions. The height of wall depends on the elevation difference across the wall and the depth of required cover on the toe side of the wall. The stem thickness and reinforcement must be sufficient to resist shears and moments due to earth pressure against the wall. The stem thickness at the top of the wall should be sufficient to permit easy placement of concrete.

The dimensions of the base, heel and toe are a function of result from the stability and strength requirements established in the design procedure. The required base width is a function of strength properties of backfill and foundation soils and the slope of backfill. The thickness of the base depends on shears and moments at sections located at the front and the back faces of the stem. The base in front of the wall should be placed below the depth of frost action, zone of seasonal variation and the depth of scour. The toe and heel lengths are governed by overturning and sliding stability requirements. Recommended trial wall dimensions given by various references are shown in Table 2.1.

2.3 Forces Acting on the Wall

The forces considered for the stability analysis of a unit width of a cantilever retaining wall are shown in Figure 2.1 (a). These include the driving-side soil force P_{SD} and water force P_{WD} against the vertical section AB at the end of the heel, the resisting-side soil force P_{SR} and water force P_{WR} against the vertical section CD at the end of toe, the effective soil force N′ and uplift force U that act vertically on the base DB, shear S along DB and the

Table 2.1 Recommended trial dimensions for cantilever walls

Parts of wall	Peck (1974)	Das (1984)	Bowles (1988)
Base			
Width (B)	0.4 to 0.65 H	0.5 to 0.7 H	0.4 to 0.7 H
Thickness	H/12 to H/8	0.1 H	H/12 to H/10
Toe length	B/3	0.1 H	B/3
Stem			
Top thickness	sufficient for placement of concrete	minimum 30 cm	minimum 20 cm prefer 30 cm
Bottom thickness	increase thickness with depth by 1/4 to 3/4 in/ft	0.1 H (same as base thickness)	H/12 to H/10 (same as base thickness)

total weight the wall components and the soil masses above the base.

The principal structural elements of the wall are the stem, heel and toe. The forces considered for the structural design of these elements are shown in Figure 2.1 (b). The forces acting on the stem are different from those acting on the wall due to difference in height (Figure 2.1)

2.4 Lateral Earth Pressure

The magnitude of lateral earth pressure is determined by the physical properties of the soil, the physical interaction between the soil and the structure and the value of displacements and deformations (Kedzi 1987)

To simplify lateral earth pressure predictions, many designers assume an active state of stress on the driving side (heel side) of the wall (Bowles 1988, Das 1984). However some engineers (e.g., Matsuo et al., 1978) and agencies (e.g., U.S. Army, 1989) recommend assuming an at-rest state of stress. The active state corresponds to the minimum lateral pressure that can develop and at-rest state implies that no deformations or displacements occur. In reality an intermediate state of stress (a state of stress between active state and at-rest state) may exist on the driving side but it is difficult to predict earth pressure under this state of stress. The passive state of stress is the

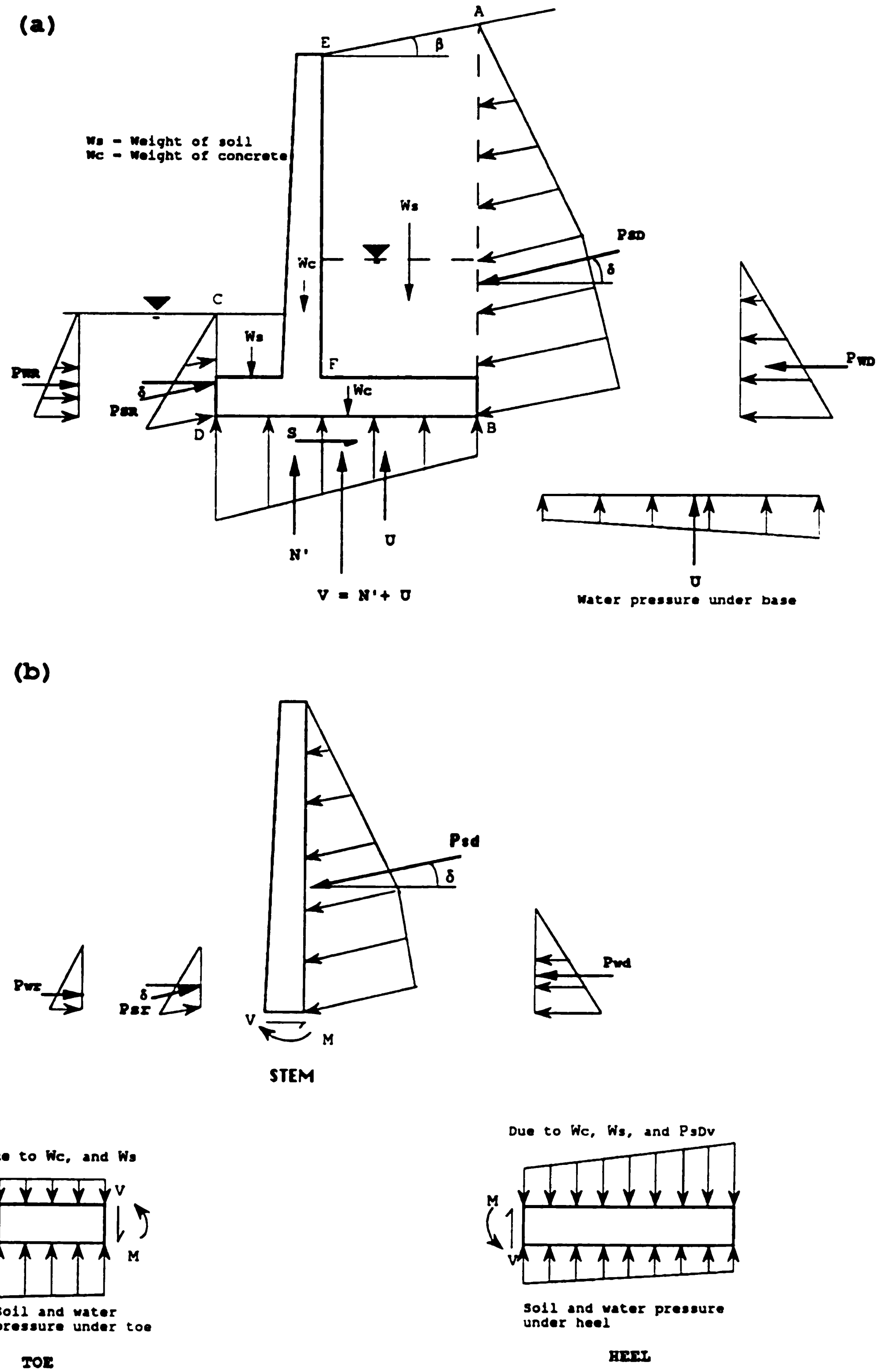


Figure 2.1 Pressure system:cantilever retaining wall:
(a) Pressures considered for external stability
(b) Pressures considered for internal stability

greatest stress that may exist on the resisting side (toe side) of the wall (Lambe and Whitman 1969) and corresponds to lateral compression to failure.

The reliability of lateral earth pressure predictions is an important factor for safe and economical design of cantilever retaining walls. Although significant research has been carried out on methods for earth pressure predictions (Terzaghi 1920, 1934 1936 and 1940, Rowe 1969, Clough and Duncan 1971, Bang and Hwang 1986, Seed and Duncan 1986); the same old classical earth pressure theories (Coulomb's and Rankine) continue to be used by designers for estimating earth pressure. To understand the difficulties associated with earth pressure prediction, the subject is discussed in the following sections.

2.4.1 Brief Historical Background

The methods currently being used in practice for earth pressure computation can be traced back to either Coulomb's or Rankine's theory of earth pressure. Coulomb obtained a minimum value of force against a wall by considering force equilibrium of a rigid failure wedge bounded by a planar failure surface, a rough frictional planar wall back face and the ground surface (Bowles 1982). Rankine considered a semi-infinite soil mass in a state of plastic equilibrium and solved for minimum and maximum stress.

Both Coulomb and Rankine assumed straight rupture planes for estimating earth pressure. Kotter in 1903 derived a differential equation governing stresses along a curved rupture-plane. Fellenius in 1927 made earth pressure calculations assuming a circular rupture-plane and Rendulic in 1935 assumed a logarithmic spiral as rupture-plane for computing earth pressure (Feld 1940, Hansen 1953)

Terzaghi (1920) was first to point out that the deformations in the soil mass must be compatible with wall movements. Ohde in 1938 investigated in detail the behavior of wall rotating about its top and bottom (Hansen 1953). The above mentioned works were mainly theoretical. Regarding experimental work, a considerable number of researchers contributed toward active earth pressure (Terzaghi 1934, Jakobson 1958, Clough and Duncan., 1971, Lee et al., 1972, Broms et al., 1972, Coyle et al., 1974, Ingold 1979, Sherif et al., 1984, Fang and Ishibashi 1986). Only a few researchers have studied passive earth pressure (Rowe et al., 1965, Rowe 1969, James et al., 1970, Shields et al., 1973).

2.4.2 Active and Passive Earth Pressure: Classical Theories

The classical earth pressure theories of Coulomb and Rankine were developed in 1776 and 1857 respectively. In one way or the other, these theories are still in use for the prediction of lateral earth pressure behind retaining structures. To check if these theories are applicable for earth pressure prediction against cantilever retaining walls, a brief review is presented in the following sections.

2.4.2.1 Coulomb's Theory (1776)

The basic approach of Coulomb's theory is to determine the minimum and maximum earth force consistent with limiting equilibrium of homogeneous and isotropic soil mass. For cohesionless soils, Coulomb assumed that a wedge of soil is formed behind walls with planar back face at minimum lateral force (Figure. 2.2). Coulomb assumed that the failure wedge acts as a rigid body and friction is developed between the back face of the wall and the failure wedge (Huntington 1957).

Coulomb's theory solves for the total lateral earth force assuming that the rupture surface is a plane (Figure 2.2) and that the shear resistance is fully mobilized along this plane. For the active case, shear on the failure plane acts against gravity and the largest total lateral earth force computed for any orientation θ represents the smallest value of lateral earth force on the back of a retaining wall. Coulomb's theory yields only the resultant force; the state of stress within the soil mass is not obtained. As moment equilibrium is not considered, the location of resultant with respect to wall height is unknown.

A linear pressure distribution increasing with depth is usually assumed behind a wall increasing with depth for the case of a level or uniformly sloping ground without

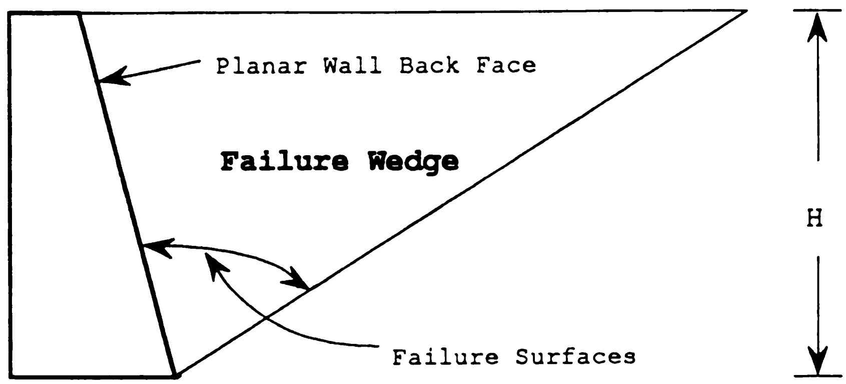


Figure 2.2 Coulomb failure wedge

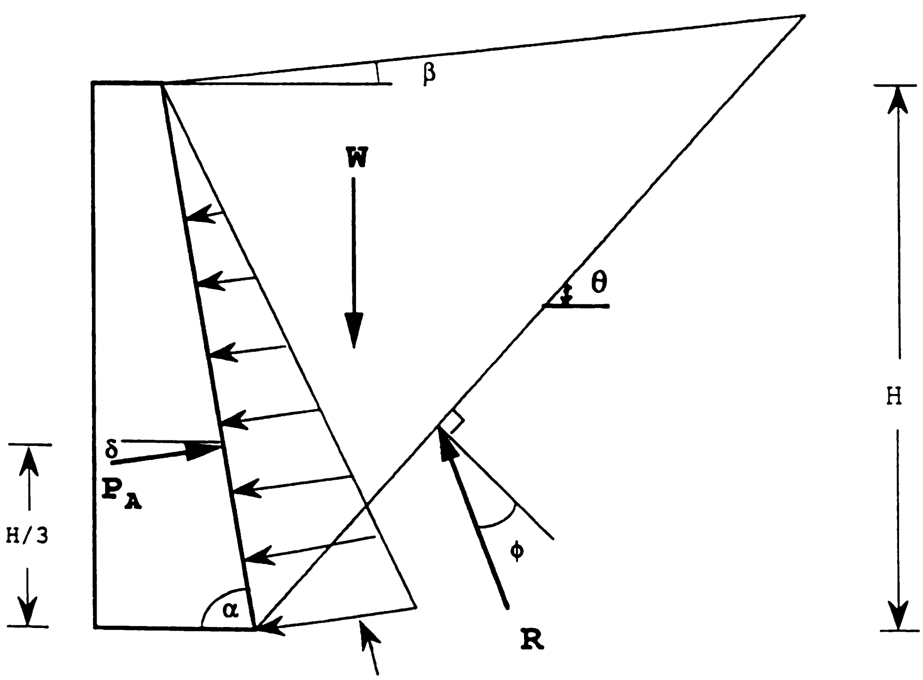


Figure 2.3 Assumed conditions for failures: Coulomb

surcharge or water table provided the soil mass is in a state of failure throughout the wedge (Wu 1975). This solution places the point of application of the resultant lateral earth force at one-third of wall height.

The magnitude of the active earth force against the wall is obtained by considering the equilibrium of the failure wedge (Figure 2.3). W is the weight of soil within the failure wedge. P_A is the resultant active force acting at the wall friction angle δ from the normal. R is the resultant of the normal and shear stresses along the rupture surface and acts at an angle of shear resistance ϕ from the normal. The analytical solution of forces acting on failure wedge yields:

$$P_A = \frac{K_a \gamma H^2}{2} \tag{2.1}$$

where γ is unit weight of the backfill, H is the wall height, K is a coefficient of active earth pressure and is given as:

$$K_a = \frac{\sin^2(\alpha+\phi)}{\sin^2\alpha \sin(\alpha-\delta)\left[1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi-\beta)}{\sin(\alpha-\delta)\sin(\alpha+\beta)}}\right]^2} \tag{2.2}$$

where α, β, ϕ and δ are angles as shown in Figure 2.3. The derivation of these equations can be found in Huntington (1957) and Bowles (1982). Similarly, the expression for the passive earth force P_p is written as:

$$P_p = \frac{K_p \gamma H^2}{2} \tag{2.3}$$

where Kp is a coefficient of passive earth pressure and is given as:

$$K_p = \frac{\sin^2(\alpha-\phi)}{\sin^2\alpha \sin(\alpha+\delta)\left[1-\sqrt{\frac{\sin(\phi+\delta)\sin(\phi+\beta)}{\sin(\alpha+\delta)\sin(\alpha+\beta)}}\right]^2} \tag{2.4}$$

For horizontal backfill, vertical wall backface (α=90 deg) and no wall friction, the coefficients of active and passive earth pressure reduce to $K_a=\tan^2(45-\phi/2)$ and $K_p=\tan^2(45+\phi/2)$ respectively. The main deficiencies in Coulomb's theory are in the assumptions involving the ideal soil and a plane rupture surface. The assumption of a plane rupture surface has a minor effect in the active case but it can lead to large errors for the passive case where wall friction is present.

The validity of Coulomb's theory for estimating lateral earth pressure behind retaining wall is limited to the case in which lateral deformation of the wall exceeds certain minimum limits sufficient to yield the backfill (Table 2.2). The deformation required to reduce the total lateral pressure of cohesionless soils to Coulomb's active state of stress is about 5 times smaller than the deformation required to establish a linear distribution of lateral pressure (Terzaghi 1934, Duncan et al. 1990). Also, the assumption of a planar wall back face is violated for cantilever retaining wall.

Table 2.2 Movements required to achieve active conditons (modified from Duncan et al. 1990)

Investigators	Wall Height (ft)	Backfill Compacted	Mode of Movement	Required Movement at Wall Top
Terzaghi (1934a)	4.9	Sand	Rotation	0.0011H
Terzaghi (1934a)	4.9	Sand	Translation	0.0011H
Terzaghi (1934a)	4.9	Sand[(1)]	Rotation	0.0020H
Broms & Ingelson (1971)	9.0	Sand	Rotation	0.0003H
Sherif & Fang (1984)	4.0	Sand	Rotation	0.0005H
Sherif & Fang (1984)	4.0	Sand[(1)]	Rotation	0.0005H
Fang & Ishibashi (1986)	3.33	Sand	Rotation	0.0003H
Fang & Ishibashi (1986)	3.33	Sand	Translation	0.0003H
Matsuo et al., (1878)	32.8	Silty Sand	Rotation	0.0006H to 0.0008H
		Slag	Rotation	0.0003H to 0.0005H

(1) Uncompacted sand

Water in the backfill results in a bilinear pressure distribution behind the wall. In this situation, Coulomb's K should be used with effective vertical stresses σ'_v to compute effective horizontal stress (i.e., $\sigma'_H=K\sigma'_v$) and additional stress caused by the water should be added to the horizontal stress to compute the total stress on the wall.

Experimental results (Fang and Ishibashi 1986) have shown that Coulomb's theory underestimates the total active force behinds walls rotating about top and bottom. However, the experimental values of total active force behind walls with translational movements is in close agreement with the values predicted by Coulomb's theory.

2.5.2.2 Rankine's Theory (1857)

Rankine considered a semi-infinite cohesionless soil mass that can develop a state of failure with the slightest deformation (Tschebatarioff 1951). He examined the effect of lateral expansion and compression of such a soil mass. The state of stress under active and passive conditions are called Rankine's states and require that there be no shearing stresses on vertical planes in a soil mass with a horizontal ground surface (Peck et al. 1974). In reality no semi-infinite mass of cohesionless soil exists. Even if it exists, it is not possible to develop a state of failure in the whole soil mass with a slight deformation as known from relation between stress and strain in the soil. However, Rankine's state of stress can be induced in wedge-shaped zone ABC (Figure 2.4).

When applying Rankine's theory to retaining walls, the inner and outer rupture surfaces must be within the soil (Huntington 1957). This implies that no sliding occurs between the back face of the wall and the soil. The soil wedge ABE remains with the wall in an elastic state of stress. The failure wedge would slide along the outer rupture surface AB instead of back face of the wall EB. As no rupture surface occurs along the back face of retaining wall; the lateral earth pressure is determined on vertical plane which passes through B. Then the resultant of active earth pressures P_A against vertical plane BD is given as:

$$P_A = \frac{K_a \gamma H^2}{2} \tag{2.5}$$

where K_a is a coefficient of active earth pressure for Rankine's conditions and is given as:

$$K_a = \cos\beta \frac{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi}}{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi}} \tag{2.6}$$

where β is backfill slope angle (Figure 2.4). Similarly the resultant passive force P_p can be computed by analogy as:

$$P_p = \frac{K_p \gamma H^2}{2} \tag{2.7}$$

where K_p is a coefficient of passive earth pressure for Rankine's conditions and it is given as:

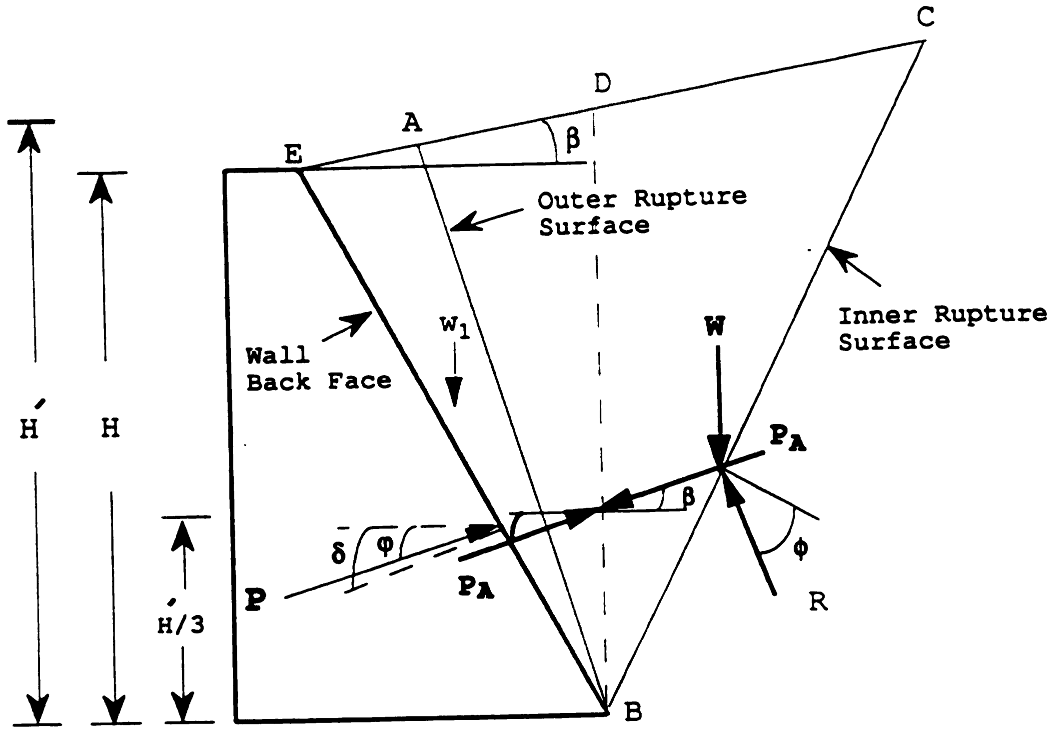


Figure 2.4 Rankine's active state of stress

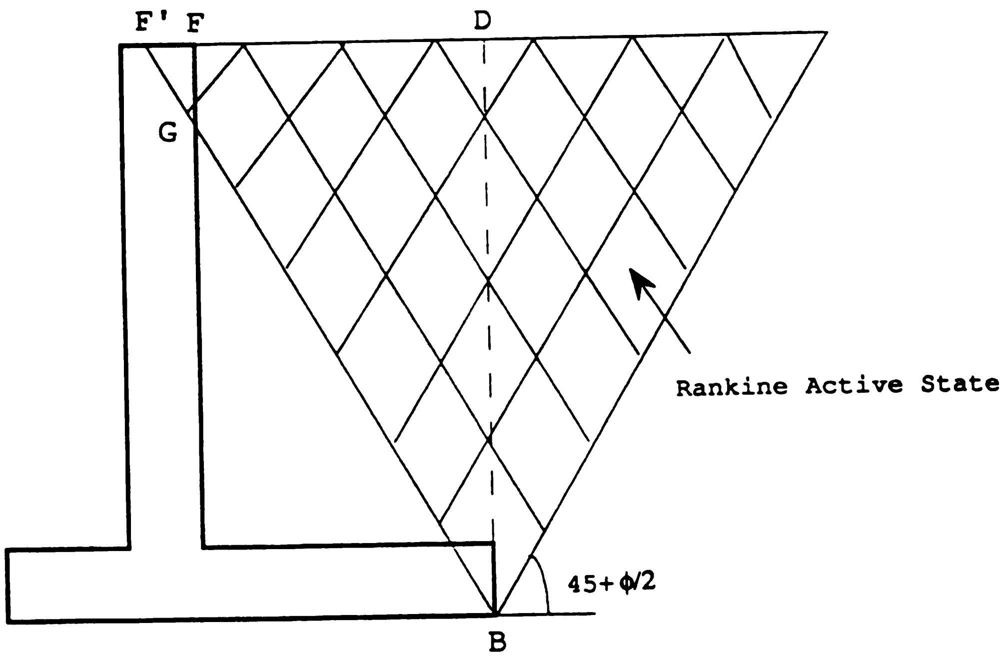


Figure 2.5 Failure of cohesionless soils behind cantilever retaining walls (from Terzaghi and Peck 1967)

$$K_a = \cos\beta \frac{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi}}{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi}} \qquad (2.8)$$

The derivation of Rankine's solution can be found in many books (e.g., Huntington 1957, Bowles 1982). In the derivation of these equations, the backfill surface EC is assumed as plane surface so that the resultant earth force on vertical plane acts parallel to the backfill surface.

For horizontal backfill, the coefficient of earth pressure reduces to $K_a = \tan^2(45 - \phi/2)$ and $K_p = \tan^2(45 + \phi/2)$ for active and passive case respectively, which is similar to Coulomb's solution for walls with horizontal backfill and no wall friction. More importantly when $\delta = \beta$ in Coulomb solution, it matches the Rankine's. The implication of this, which is often misstated, is that Rankine analysis assumes friction develop on vertical plane equal to slope angle.

The magnitude of the resultant earth force P on the back of the wall is determined by combining the resultant of lateral earth pressure P_A on vertical plane BD and the weight of the soil w_1 between the plane AB and the back of the wall (Figure 2.4). The deviation of P from the normal to the back of the wall is an angle φ and angle φ must be less than δ for Rankine's theory to apply (Huntington 1957).

Rankine's theory yields the solution for the active and passive state of stress in a soil mass. Therefore, the earth pressure distribution and the resultant earth force are known, provided there is no violation of assumptions on which this theory is based. Rankine's theory implies linear distribution of earth pressure with depth behind the wall and places the resultant of forces one-third of height H' for the case of a wall without considering the effect of water presence in the backfill (Figure 2.4).

Terzaghi (1943) pointed out that the use of Rankine's theory for lateral earth pressure predictions should be discontinued because its fundamental assumptions are not compatible with the known relation between stress and strain in the soil. However, for cantilever retaining walls with horizontal backfill, Terzaghi and Peck (1967) state that the deformation condition for the active Rankine state is almost satisfied. In this case the soil fails along the two planes rising from the heel of the wall at an angle of $45+\phi/2$ with the horizontal (Figure 2.5).

2.4.3 At-Rest Earth Pressure

Non-yielding walls such as bridge abutments experience at-rest or even higher pressures because of their rigidity. For such walls with normally consolidated cohesionless backfills and horizontal backfill surface, the coefficient of at-rest pressure K_o can be estimated using Jaky's equation as (Jaky 1944):

$$K_o=1-\sin\phi \tag{2.9}$$

where ϕ is drained friction angle of the backfill.

Experimental results suggest that Jaky's equation is valid only when backfill is deposited at its loosest state behind retaining walls (Sherif et al., 1984).

For normally consolidated sloping backfills, the equation proposed in the Danish Code (Danish Geotechnical Institute 1978) can be used for computing at-rest earth pressure coefficient, $K_{o\beta}$ as:

$$K_{o\beta}=K_o(1+\sin\beta) \tag{2.10}$$

The stress distribution behind non-yielding walls is assumed linear. Where a water table is not present, the resultant force acts at one-third of wall height from the wall base.

2.4.4 Earth Pressure at Intermediate Active State

An intermediate active state corresponds to the state of stress between active and at-rest states. The prediction of lateral earth pressure at intermediate active state is difficult to estimate due to partial mobilization of shear strength of the backfill.

Some researchers made use of finite element methods (Clough and Duncan 1971, Duncan et al., 1990) or developed analytical methods (Bang 1985, Bang and Hwang 1986) to predict earth pressure at any intermediate active state. However, these methods are not being used in routine design of retaining structures due to uncertainty in assumptions on which these methods are based.

2.4.5 Factor Affecting Actual Earth Pressure

The main factors that affect actual earth pressure include wall movement, wall friction, water in the backfill, compaction of the backfill, surcharges and seasonal variation. These are discussed briefly in the following sections.

2.4.5.1 Wall Movement

Under service conditions a rigid retaining wall possibly can rotate about its base, its top, its middle, or another point; it can translate or there can be a combination of these modes. It is also possible that wall may not yield at all. Terzaghi (1934), is believed to be the first to conclude from his large-scale earth pressure tests that the lateral earth pressure distribution behind retaining walls is associated with the type and the magnitude of wall movement.

Earth pressure distribution behind a wall rotating about its base is considered as linear (Terzaghi 1934). For wall rotating about its top, Wu (1966) derived and expression that yields a semi-parabolic pressure distribution. Kezdi (1975) reports an approximate method developed by Rendulic for a translating walls. Rendulic's method yields an almost parabolic pressure distribution behind the wall.

Harr (1977) summarizes Dubrova's method for predicting earth pressure for walls rotating about any point. Experimental results of Sherif et al., (1984), Fang et al., (1986) are in good agreement with theoretical pressure distributions. Active conditions are justified for: (1) translating wall, (2) wall rotating about its top or bottom, and (3) wall yields under combine action of translation and rotation. It is reasonable to use TWALL when wall yields sufficiently to develop active conditions behind the wall or for at-rest conditions for non-yielding walls.

2.4.5.2 Wall Friction

A relative movement between a retaining wall and its backfill develops shear forces between the face of the wall and the backfill. These are termed wall friction (Lambe and Whitman 1969). In the case of a cantilever retaining wall, relative movement along a vertical plane through the end of the heel also results in vertical shear forces along the plane. Although this plane is not a wall surface, this effect is also loosely termed "wall friction".

The wall friction depends on roughness of the wall, amount and direction of the wall movement, soil properties of the backfill and inclination of ground surface behind the wall. The wall friction is also influenced by the settlement of the structure and the backfill soil (Brandl 1987).

The maximum value of wall friction may not occur simultaneously with the maximum shearing resistance and the value of wall friction may vary across the wall (Bowles 1982). The effect of change in wall friction angle for full scale reinforced concrete cantilever retaining walls with horizontal backfill was studied by Coyle et al. (1972) during their field tests. It was found that wall friction angle between 1/3ϕ to 2/3ϕ is a good approximation for computing lateral earth pressure using Coulombs's theory.

The wall friction affects the magnitude and the direction of earth pressure. The effect of friction on the direction of active pressure is more significant than on the magnitude. Lambe and Whitman (1969) report that wall friction changes the active pressure by only 7 percent but decrease the horizontal component of this pressure by 24 percent when the wall friction angle was varied from 0 to 35 degrees.

2.4.5.3 Water in the Backfill

The presence of water in the wall backfill without compensating water in front substantially increases total pressure because the coefficient K for water is unity. The distribution of pressure on a retaining wall due to water is hydrostatic and the resultant water force acts at one-third the water height from wall base. The effective earth force acts above one-third of wall height due to the presence of water in the backfill. The combine force due to soil and water acts below the one-third of wall height. Because of the buoyant effect of water on soil particles, the weight of submerged soil is reduced by an amount equal to the weight of water displaced by the soil particles.

2.4.5.5 Surcharges

Surcharges such as infinite uniformly distributed loads, concentrated line loads and strip loads increase lateral earth pressure on retaining structures. Only the effect of infinite uniformly distributed loads on cantilever retaining walls is considered in this study. The lateral earth pressure exerted by a uniformly distributed surcharge q_o from the surface of the backfill downward is given as:

$$p_o = K\ q_o \qquad (2.11)$$

where K is coefficient of earth pressure and has the same value as that used for the determination of lateral earth pressure exerted by the soil. A uniform surcharge results in a rectangular pressure distribution diagram which should be added to the lateral earth pressure diagram of the backfill. Methods for computing the increase in lateral earth pressure due to other types of surcharge are discussed in many books on soil mechanics (e.g., Tschebatarioff 1973, Wu 1976, Das 1984).

2.4.5.6 Seasonal Variation

Seasonal variations affect the magnitude and the distribution of earth pressure mainly because of changes in temperature, freezing of backfill and heavy rainfall. Field test results show about 30 percent variation of earth pressure due to seasonal variations (Terzaghi and Peck 1967). Similar observations were made by Coyle et al., (1972) and Wright et al., (1975) during their five year study on cantilever and precast panel walls.

The earth pressure usually increases in the summer and decreases in the winter (Duncan et al., 1990). The warm front face of a wall in the summer expands relative to the back face and causes the wall to deflect back against the fill. The result is an increase in earth pressure. In the winter the pressure is reversed. However, the earth pressure also increases in winter due to expansion of water in the backfill voids due to freezing (Rehnman and Broms 1972). Rehnman and Broms (1972) also observed about 50 percent increase in earth pressure due to simulated rain fall at the rate of 5 inches per hours. TWALL allows the designer to specify a water table in the backfill to simulate the effects of any such rainfall.

2.4.6 Field Measurement of Lateral Earth Pressure

Many researchers have reported measured earth pressure on walls as higher than active pressures (Goulds 1970, Broms and Angelson 1971). Field measurements of lateral earth pressure were conducted by Coyle et al. (1974) and Wright et al. (1975) on an 18.25 feet high cantilever retaining wall with cohesionless backfill. The wall was founded on piles and the base was restrained to a great extent due to pile foundation.

The measured pressures agreed with theoretical pressures in the upper part of the wall but were found to be close to at-rest values in the lower part of the wall. This is expected due to the safety factors incorporated in the design; the wall did not move far enough for the pressure to reduce to active value. Such measurements supports the recent trends (para 1.3.2.4 and Chapter 6) toward designing for at-rest conditions.

2.4.7. Location of Resultant Earth Force

The resultant earth force has been generally observed to be higher than one-third of wall height from the base as inferred from earth pressure theories. Terzaghi (1934) found that the resultant was at 0.4 to 0.45H above the wall base under active conditions but as the wall continued to move outward, the resultant dropped to 0.33H with triangular distribution. The wall movement required to get a triangular distribution was observed to be much higher than the movement required to reduce earth force to its active value. It shows that even under active conditions, the earth pressure distribution is not hydrostatic and the resultant is expected to act above the lower third point.

Sherif et al., (1982), Sherif et al., (1984) and Fang and Ishibasi (1986) also observed the similar range of locations of resultant earth force. Handy (1985) reports the effect of soil arching on earth pressure behind retaining walls. According to him, initially the magnitude of earth pressure exceeds the at-rest values and the resultant of lateral earth pressures acts at 0.33H because of triangular pressure distribution. But with the wall movement, the pressure distribution becomes parabolic and the pressure falls below the active values but the point of application of the resultant rises to 0.42H.

For walls with foundation restraints, the resultant is expected to act below 0.33H. Wright et al., (1975) recommend point of application of resultant earth force at 0.265H for walls founded on piles.

2.5 Foundation Pressure

Lateral earth pressure causes an eccentric loading on the base of retaining structures. The soil pressure distribution along the bottom of the wall base can be computed by assuming a linear variation and using mechanics formulas for combined bending and axial stresses. Taking moments about an axis perpendicular to the wall base of width B and of unit length, the minimum and maximum base pressures are given as (Bowles 1982):

$$q = \frac{V}{B}\left(1 \pm \frac{6e}{B}\right) \tag{2.12}$$

in which

$e=(B/2)-x$ and $x=(M_r-M_o)/V$

where V is the sum of vertical forces at the bottom of the base, e is eccentricity or a horizontal distance from the middle of the base to a point where V acts, x is the distance from the free toe end to the point of action of V (Figure 2.6), M_r and M_o are resisting moment and overturning moment respectively. The above is easily extended below the water table by taking separate pressure distributions for N′ and U where N′=(V-U).

The wall base is sized such that e is less than or equal to B/6 so that the resultant of vertical forces remains within the middle third of the base. This assures compressive contact pressure across the entire base. This solution is applicable when the resultant acts on the toe side of the wall from base mid point. The pressure distribution is assumed to be linear and the area of pressure diagram should equal the total vertical load.

2.6 Wall Stability

To ensure external stability, a cantilever retaining wall must be found safe against overturning, sliding, and

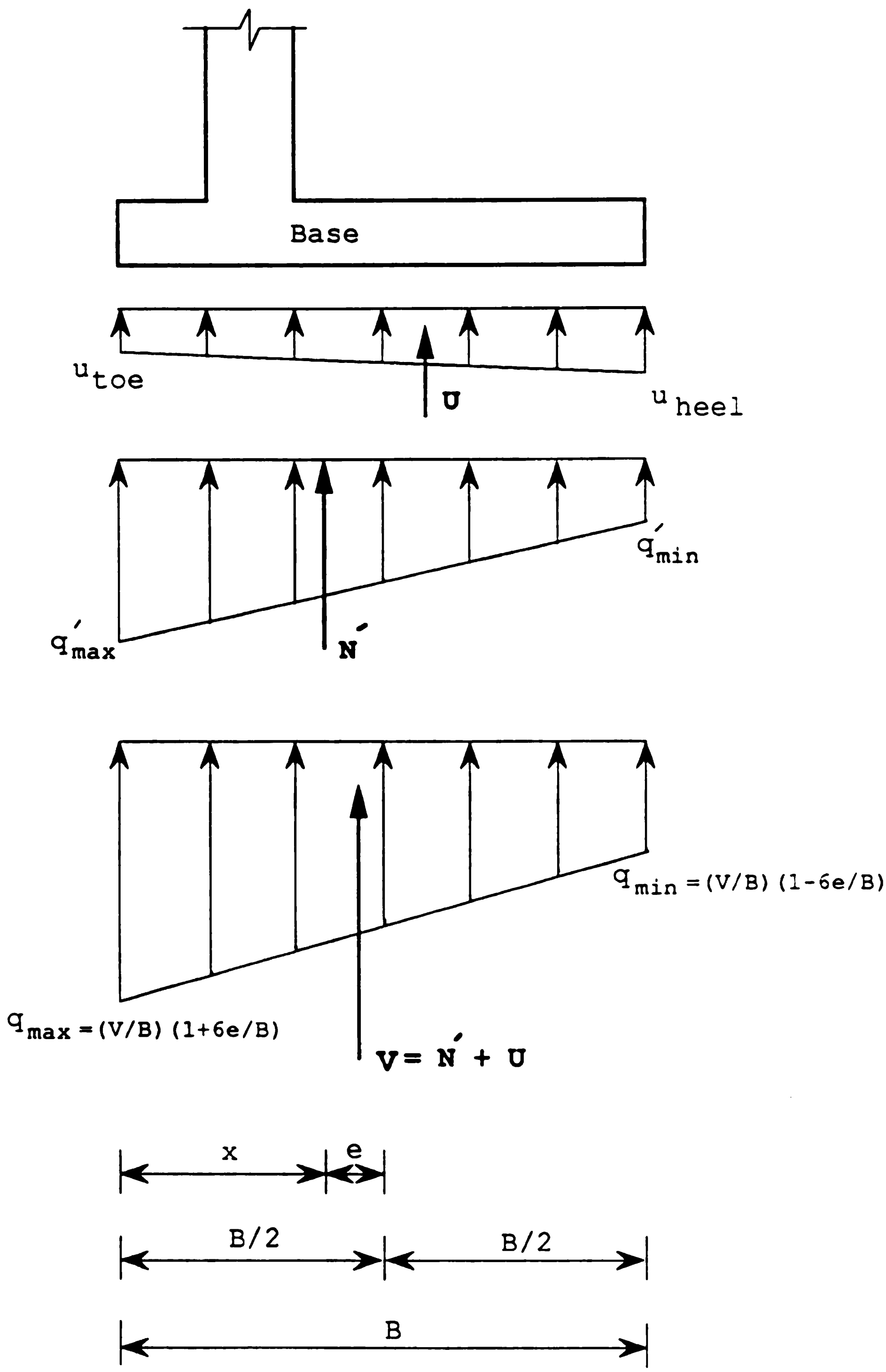


Figure 2.6 Pressure distribution under the base

bearing capacity failures and excessive base settlements should not be expected. The steel reinforcement of stem, heel and toe should be sufficient to ensure internal stability against applied bending moments and shears.

2.6.1 External Stability

2.6.1.1 Stability Against Overturning

Stability against overturning is obtained by ensuring that the moments available to resist wall overturning are greater than the moments tending to overturn the wall (Wu 1975). The force system on the wall is shown in Figure 2.7. Overturning is checked by summing moments about point O on the toe side of the wall. Neglecting any vertical components on the toe side, the sum of vertical forces is:

$$\Sigma W = W_s + W_c + P_{SDV} \qquad (2.13)$$

where W_s and W_c are weights of backfill and wall concrete (base and stem) respectively and P_{SDV} is a driving-side vertical friction component resisting overturning and taken as $P_{SDV}=P_{SD}\sin\delta$. Then, the resisting moment is given as:

$$M_r = \Sigma W\ L_w + P_{WR}\ L_{WR} \qquad (2.14)$$

in which P_{WR} is a horizontal water force on resisting side of the wall, L_w and L_{WR} are moment arms as shown in Figure 2.7.

The development of full passive earth force P_p on the toe side of the wall requires large wall deformations which may not be desirable in a real structure. For a wall in equilibrium the mobilized resisting force P_{SR} on the toe side can be almost equal to the passive earth force. Base shear S is developed at much smaller wall movements than P_{SR}. Thus, the passive resistance in front of the wall is developed only after the full mobilization of base shear. The resisting force P_{SR} is neglected in TWALL because a fill may be placed behind the wall before it is placed in front of the wall or cut may be made in front of the wall during its service life. If P_{SR} is to be included in the analysis, the U.S. Army Corps of Engineers recommends limiting its value to half the P_p (U.S. Army, 1989). The weight of soil above the toe is also neglected because of its small contribution toward the wall stability and uncertainty that it will remain present during the life of the structure.

The forces tending to overturn the wall include a driving-side earth force P_{SDH} acting at a distance L_{SD} from the wall base, an uplift force U acting vertically beneath the base at distance L_u from the toe, the resisting-side water force P_{WD} acting at a distance L_{WD} from the base. Then the overturning moment is given as:

$$M_o = P_{SDH} L_{SD} + U L_u + P_{WD} L_{WD} \tag{2.15}$$

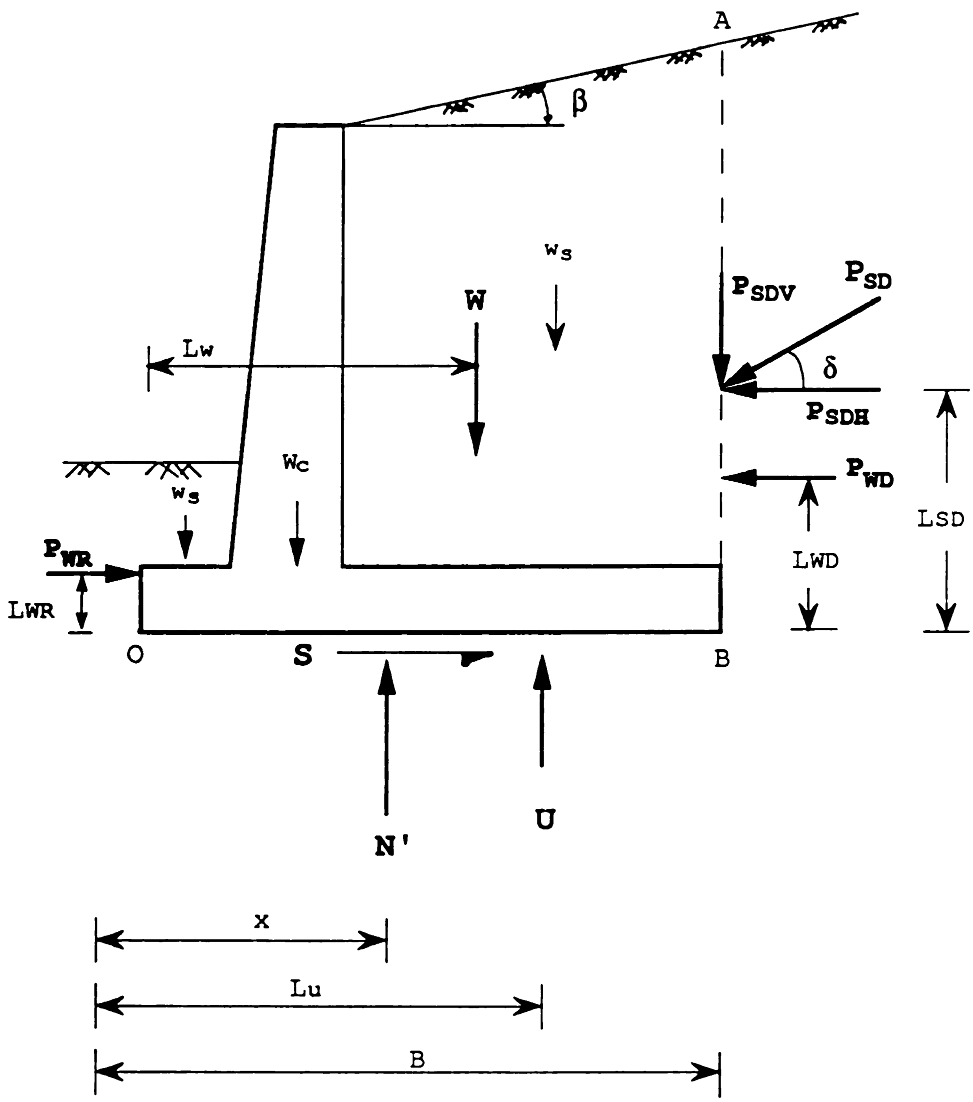


Figure 2.7 Force system: external stability

in which $P_{SDH} = P_{SD} \cos\delta$.

where δ is a wall friction angle. For Rankine analysis δ is taken as the backfill slope angle β and for Coulomb analysis, it can be taken as $\beta<\delta<\phi$ for overturning analysis.

The factor of safety against overturning is the ratio of resisting moments to the overturning moments and is computed as:

$$F.S.(o) = \frac{M_r}{M_o} \tag{2.16}$$

A safety factor of 1.5 to 2.0 depending on wall importance, is considered adequate for safety against overturning (Wu 1975, Bowles 1988).

The concept of resultant ratio is used by the Corps of Engineers for evaluating wall stability against overturning (U.S. Army, 1989). The resultant ratio is the ratio of the distance x to the base width B as shown in Figure 2.7. The wall founded on soil is considered safe against overturning if the resultant ratio is between 1/3 to 2/3. In other words, if the resultant force on the foundation passes through the middle third of the wall base.

From the previous discussion on lateral earth pressure, it can be concluded that total earth force P_{SD} may vary between active and at-rest values depending on wall movements. Compaction and other such factors can cause pressures even higher than at-rest pressure. For active conditions, Coulomb's or Rankine's theory can be used for predicting P_{SD}. For at-rest conditions, Jaky's equation with some modification for sloping backfill as suggested in Danish Code may be used for estimating P_{SD}.

2.6.1.2 Stability Against Sliding

The horizontal earth force P_{SDH} and net horizontal water force (P_{WD}-P_{WR}) on vertical plane AB (Figure 2.7) cause the wall to tend to slide forward. The forces that resist sliding are the friction force S beneath the base and the resisting-side soil force P_{SR} in front of the wall. In TWALL, P_{SR} is also neglected in sliding stability analysis for the same reasons as mentioned earlier. The resisting force against sliding is computed as:

$$F_R = N'\tan\delta_b \qquad (2.17)$$

where N' is effective vertical force beneath wall base and given as $N'=V-U$, δ_b is friction angle between the wall base and foundation soil. The friction angle between wall base and foundation δ_b may be taken as equal to soil friction angle ϕ because wet concrete adheres sufficiently to the foundation soil and the effective developed resistance can be considered between soil to soil (Bowles 1982).

The factor of safety against sliding is a ratio of forces that resist sliding to driving forces and may be computed as:

$$F.S.(s) = \frac{F_R}{P_H} \tag{2.18}$$

where $P_H = P_{SDH} + (P_{WD} - P_{WR})$

A safety factor of 1.5 is considered adequate for safety against sliding failures (Wu 1975, Bowles 1988)

The friction between wall base and foundation soil depends on the shear strength of foundation soil. If the resistance to wall sliding is not sufficient to offset the driving forces, the base length may be increased or a key can be added to the base. The shear surface may follow different shapes depending on the location and length of the key.

2.6.1.3 Bearing Capacity

The base of the wall should be sized to ensure that the actual contact pressure does not exceed the bearing capacity of the foundation soil. The wall is considered safe against bearing capacity if the ultimate bearing force Q_{ult} exceeds the actual effective soil force N′ by a sufficient factor of safety.

The embedment depth for cantilever retaining walls is usually less than the base width and the wall length is considerably larger than the base width. Assuming the base sand is reasonably dense, the mode of bearing capacity failure of a cantilever retaining wall can be considered as general shear failure of a shallow strip footing. Thus, the ultimate bearing force of foundation soil may be computed using Meyerhof's bearing capacity equation (Bowles 1982). The shape factors are neglected since the base is considered as strip footing and depth factors can be ignored being slightly conservative. Then, the equation for bearing capacity can be written as:

$$Q_{ult} = B'[cN_c i_c + qN_q i_q + 0.5\gamma_e B' N_\gamma i_\gamma] \qquad (2.19)$$

where

B'= effective foundation width = B-2e

c = cohesion of foundation soil

q = effective overburden stress

γ_e = effective unit weight of foundation soil taking into account the variation of water table below the wall base to a depth He (Bowles 1982)

$\gamma_e = (2He-dw)dw/(He^2\ \gamma_{wet}) + (\gamma'/He)(He-dw)^2$

in which

He = $0.5B\tan(45+\phi/2)$

dw = depth of water table below wall base

γ_{wet} = wet unit weight of soil in depth dw

γ' = submerged unit weight = $\gamma_{sat}-\gamma_w$

N_c, N_q and N_γ are bearing capacity factors for a horizontal strip footing under vertical loading and are given as:

$N_q = [e^{\pi \tan\phi}] \tan^2(45+\phi/2)$

$N_c = (N_q-1)\cot\phi$

$N_\gamma = (N_q-1)\tan(1.4\phi)$

i_c, i_q and i_γ are inclination factors that account for the shear resistance along the foundation slip plane on the toe side of the wall and are given as:

$i_c = i_q = [1-\theta/90]^2$

$i_\gamma = [1-\theta/\phi]^2$

$\theta = \tan^{-1} (P_{AH}/V)$

where θ is an angle of resultant measured from the vertical axis.

The factor of safety is a ratio of ultimate bearing capacity of foundation soil Q_{ult} to the actual effective soil force N′ under the base. A minimum safety factor of 2 for cohesionless soils and 3 for cohesive soils is considered adequate for safety against bearing capacity failures (Bowles 1988). The Corps recommends a minimum safety factor of 3 for all type of soils (U.S. Army, 1989). The factor of safety against bearing capacity failure may be computed as:

$$F.S.(b) = \frac{Q_{ult}}{N'} \qquad (2.20)$$

2.6.1.4 Settlements

For walls founded on granular soils, most of the expected settlement occurs during the construction period and settlement is not a serious problem (Bowles 1988). But for walls founded on or underlain by cohesive soils, a settlement analysis is required if the applied pressure exceeds the preconsolidation pressure of the foundation soil. The analysis is based on the computed pressure distribution along the bottom of the base.

Walls on compressible soils may settle toward the backfill and significantly increase the earth pressure on the back face of the wall (Terzaghi and Pack 1967). To keep the settlement relatively uniform in such soils, the resultant force should be kept near the middle of the base (Bowles 1982). Excessive differential settlements also contribute toward the instability of the wall. Settlement computations are beyond the scope of this study. However, heuristics incorporated in TWALL minimize differential settlement by keeping the base resultant near the middle of the base.

2.6.2 Structural Design

2.6.2.1 Basis

The structural design of a cantilever wall is based on factored service loads in recognition of the possibility of an increase above service load conditions. The American Concrete Institute (ACI) Code 318-89 specifies that cantilever walls should be designed according to flexural design provisions of the Code but the application of overload factors is not directly apparent. An overload factor is a number from 0.9 to 1.7 that is to be multiplied with the structural loads to satisfy the safety provisions of ACI Code. The overload factors given in ACI 9.2.4 for the design of members to resist earth pressure cannot be applied as easily to retaining walls as to the members in building.

There can be many different combinations of factored dead load D and live load L and the earth pressure. The ACI Code interpretation are: (1) the dead load that increases design moments should be multiplied by 1.4, such as for heel, (2) the dead load such as earth over heel that reduces the effect of earth pressure should be multiplied by 0.9, (3) the effect of earth pressure such as soil pressure under heel should be multiplied by 1.7 (ACI 318-89). Obviously, these factored load states seem to be quite confusing to the designer and perhaps contradictory.

To simplify the Code interpretation, many engineers (Wang et al., 1985, Ferguson et al., 1988, Nilson et al., 1986) neglect soil pressure under the heel and use an overload factor 1.4 for dead loads over the heel. The other reasons given for this neglect are that the actual soil pressure under the heel is very small and its distribution is non-linear. This reasoning has been generally based on a pressure distribution as shown in Figure 2.8 (a).

There is also a possibility that the upward soil pressure under the heel is distributed as shown in Figure 2.8 (b). This distribution results when the resultant of forces

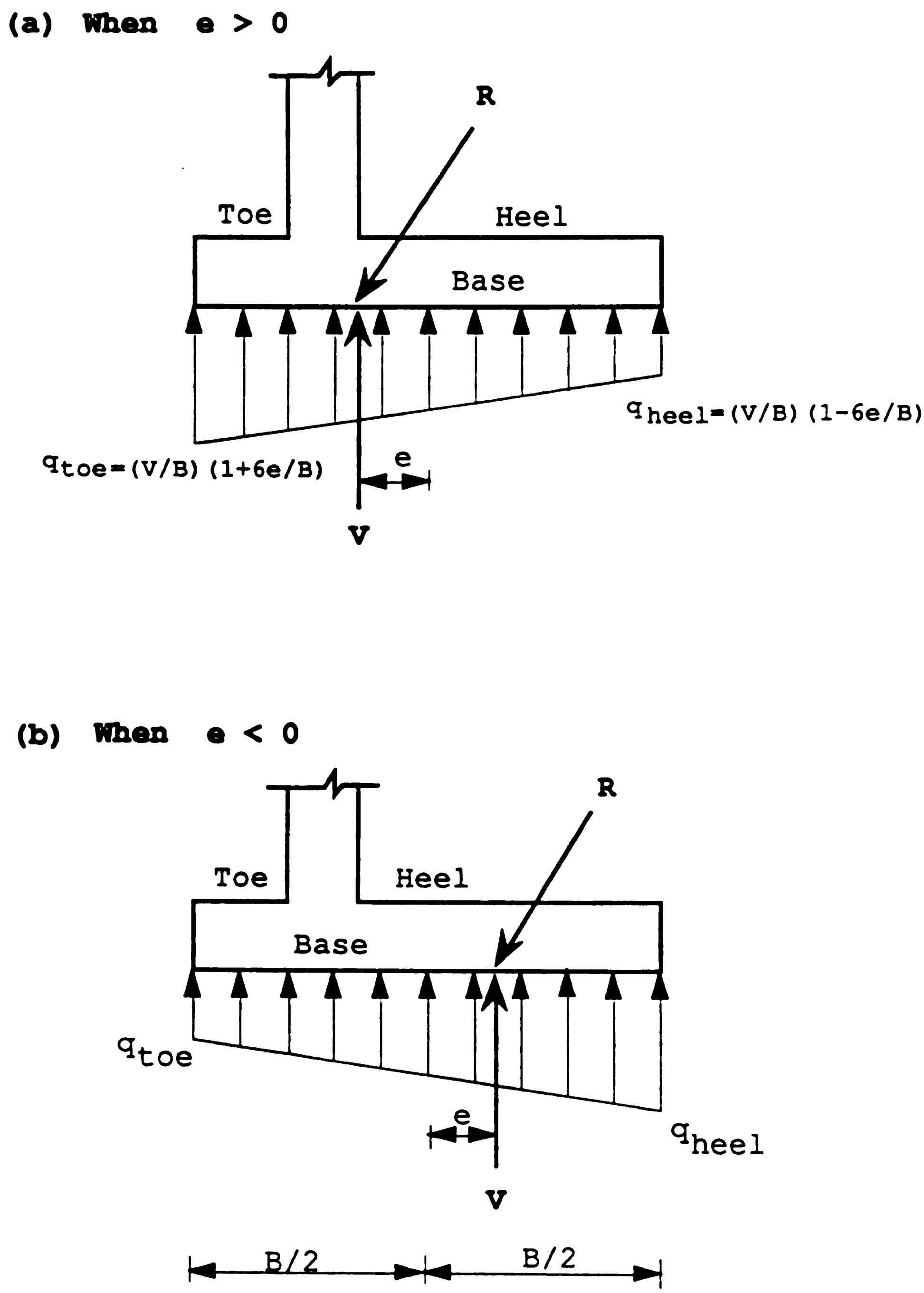


Figure 2.8 Effect of eccentricity on distribution of soil pressure under the base

R acts on the heel side from mid point of the base. In this case, neglect of soil pressure under the heel can lead to very conservative heel thickness. The overload factors commonly recommended by the structural engineers for the design of cantilever retaining walls are given in Table 2.3 (Wang et al., 1985, McCormac 1986).

Many engineers (e.g., Newman 1976, Bowles 1988) recommend not to neglect soil pressure under the heel for heel design and subtract it from loads over the heel before applying overload factors. Similarly, for toe design, the loads over the toe are subtracted from the upward soil pressure before applying load factors. Generally, the same load factors are used for the design of stem, heel and toe. The overload factors can vary between 1.7 to 1.9, depending on importance of retaining structure and assumptions, such as active or at-rest, made for earth pressure computations.

Table 2.3. Overload factors

Wall Part	Type of loading	load factor
Stem	Earth pressure	1.7
Heel	Soil and water over heel Weight of heel Surcharges	1.4 1.4 1.7
Toe	Weight of toe Soil pressure under toe	0.9 1.7

The structural design of stem, heel and stem is discussed in the following sections. The design is restricted to the calculation of pressures, shears, moments and required area of steel. The discussion on development length, splicing and other minor details is beyond the scope of this study.

2.6.2.2 Stem Design

The stem is considered as a cantilever beam of unit width for computing steel area and treated as a cantilever slab while making checks for shear (Nilson et al., 1986). The shear and moment at the base of stem due to lateral earth pressure are computed and are used to determine the stem thickness and required steel reinforcement. The critical section for bending moment is taken at the bottom of stem and critical section for shear can be taken at distance d from the bottom of stem (ACI-11.1.3.1), where d is a distance from mid of reinforcement to the front face of the stem where stem joins the base.

To make the calculations simple, many engineers usually take critical section for both shear and moment at the bottom of stem (McCormac 1986, Bowles 1988). The critical section for shear taken at stem bottom results in a slightly thicker stem which helps the stability of the wall but may reduce wall movement essential to develop active conditions behind the wall.

The earth pressure on the stem due to backfill is assumed to vary bilinearly in the presence of water with depth from wall top and attains maximum value at a depth equal to the height of stem H_s. The pressure due to water varies linearly in proportion to the depth of water above the base. The weight of stem causes some axial compression which can be neglected being very small. Then, the maximum pressure that acts at the bottom of the stem is given as:

$$p=[\gamma(H_s-H_{wD})+\gamma'(H_{wD}-t_b)]K+\gamma_w(H_{wD}-t_b)-\gamma_w(H_{wR}-t_b) \tag{2.21}$$

where K is coefficient of earth pressure which can vary between active and at-rest values and γ and γ' are effective and submerged unit weights of backfill soil respectively. H_{wD} and H_{wR} are water table heights from the bottom of wall base on driving and resisting side respectively, t_b is base thickness and γ_w is unit of weight of water. The shears and moments at the bottom of stem can be given as:

$$V = P_{sd}\cos\delta + P_{wd} - P_{wr} \tag{2.22}$$

$$M = P_{sd}\cos\delta\ L_{sd} + P_{wd}\ L_{wd} + P_{wr}\ L_{wr} \tag{2.23}$$

where P_{sd} is lateral earth force on driving side of the stem, δ is wall friction angle, P_{wd} and P_{wr} are horizontal water forces on heel and toe side of the wall respectively. L_s, L_{wd} and L_{wr} are moment arms as shown in Figure 2.9. Lateral earth force P_{sr} on toe side is neglected because of uncertainties associated with its presence.

The bending moment requires the use of vertical

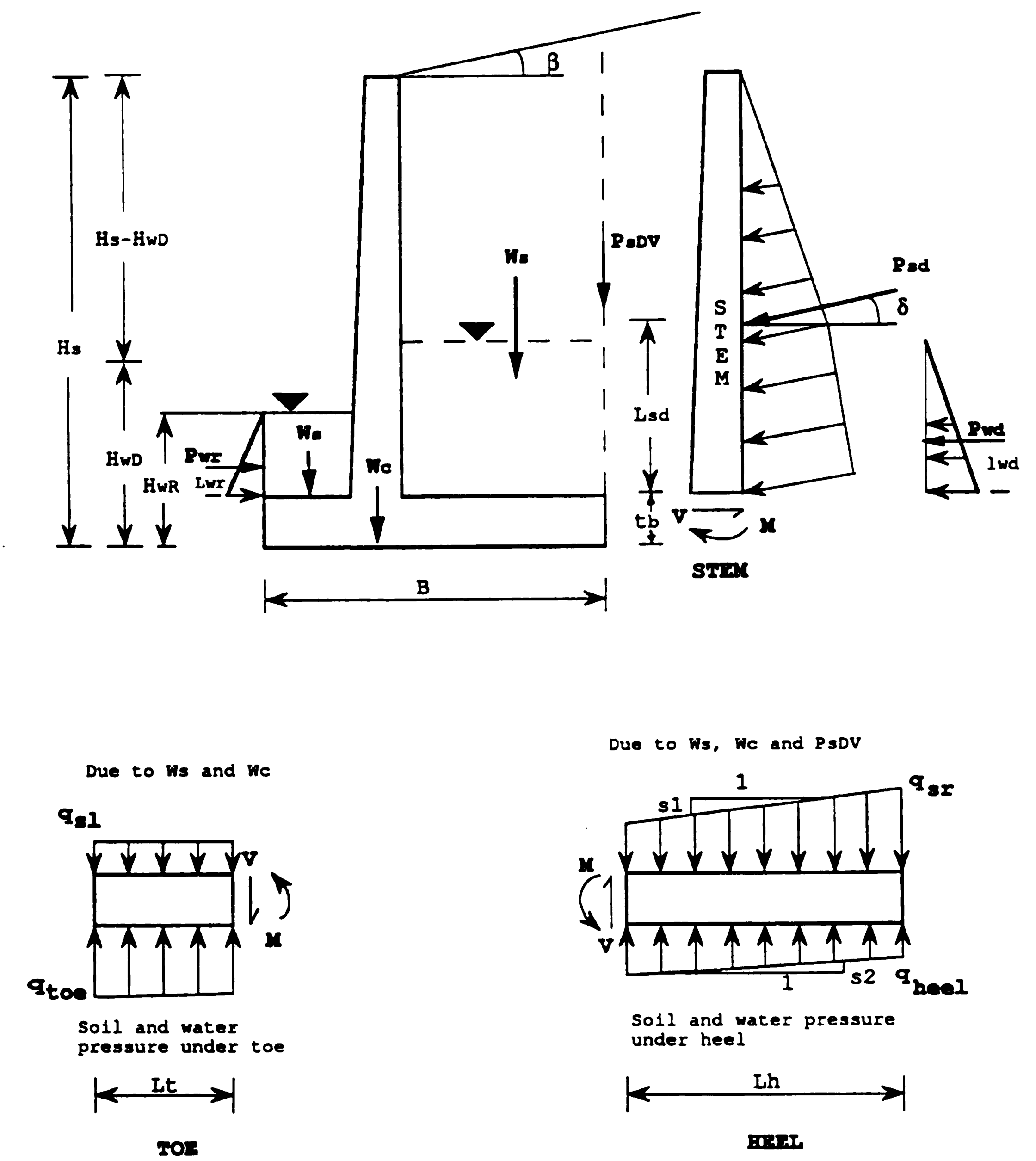


Figure 2.9 Forces considered for the structural design of stem heel and toe

reinforcement on the backfill side of the stem. In addition, temperature and shrinkage reinforcement must be provided according to ACI-14.3.3. Two-third of temperature and shrinkage steel may be used on the front face because of higher temperature variation. There should be just enough vertical steel on front face to support the horizontal reinforcement

2.6.2.3 Heel Design

The heel is designed as a cantilever beam for the downward forces acting over the heel and upward soil pressure which acts under the heel. The forces that are considered over the heel include the weight of backfill, weight of the heel itself, vertical component of lateral earth force and weight of water. The forces acting over the heel tend to push the heel downward into the foundation soil. The necessary upward reaction to hold it attached with the stem is provided by the upward soil and water pressures under the heel and a shear force at the intersection with the stem.

The critical section for bending moment is taken at the center of the stem steel because the plane of weakness is likely to occur at stem steel rather than at the back face of stem where it joins heel (Wang et al., 1985). The Code (ACI-11.1.3) allows the critical section for shear to be taken at distance d from the face only when compression is induced in the end region due to support reaction. In the present case, tension is induced in the concrete where heel joins the stem. Therefore, many designers consider the critical section for shear at a point where heel joins the stem. The shear usually controls the heel thickness (Wang et al., 1985, McCormac 1986).

The shear and moment at the critical sections are computed to determine heel thickness and steel reinforcement. The expressions for computing pressure q, shear V and moment M, at the critical sections are given as:

$$q = q_{sr} - q_{heel} - (s1 + s2) L_h \tag{2.24}$$

$$V = (q_{sr} - q_{heel}) L_h - (s1 + s2) \frac{L_h^2}{2} \tag{2.25}$$

$$M = (q_{sr} - q_{heel}) \frac{(L_h + L_{h1})^2}{2} - (s1 + s2) \frac{(L_h + L_{h1})^3}{6} \tag{2.26}$$

where q_{sr} is pressure over the free end of heel due to downward acting loads, q_{heel} is upward soil pressure at the end of heel, s1 and s2 are slopes of pressure distribution over and below the heel respectively, L_h is the heel length and L_{h1} is the distance from stem face to the center vertical tensile steel of the stem (Figure 2.9).

The base is not subjected to extreme temperature as it is well below the ground surface. Therefore, the requirement of temperature and shrinkage steel is very small and mainly this steel acts as spacers bars for the main flexural steel. (McCormac 1986, Nilson et al., 1986)

2.6.2.4 Toe Design

The toe is also designed as a cantilever beam for the weight of soil, water over the toe and the weight of toe itself all acting downward and the soil pressure under the toe acting upward. The critical section for moment is taken at a point where toe joins the stem and the critical section for shear can be taken at a distance d from the face of the stem (Wang et al., 1985). It is convenient to take the critical section at the face of support because usually the toe length is small. The thickness of toe need not be same as the thickness of heel but most designers make it same (McCormac 1986, Bowles 1988) for ease of construction.

The shear and moment at the critical section are computed to determine toe thickness and reinforcement. The pressure q, shear V and moment M, at the face of stem where toe and stem join can be computed as:

$$q = q_{toe} - q_{s1} - s2 L_t \qquad (2.27)$$

$$V = (q_{toe} - q_{s1}) L_t - s2 \frac{L_t^2}{2} \qquad (2.28)$$

$$M = (q_{toe} - q_{s1}) \frac{L_t^2}{2} - s2 \frac{L_t^3}{6} \qquad (2.29)$$

where q_{sl} is pressure over the toe, q_{toe} is upward soil and water pressures at far end of the toe, s2 is slope of upward soil pressure distribution under the base, L_t is the toe length (Figure 2.9).

2.6.2.5 Moment Capacity

In this study, the cantilever retaining wall is designed for shear and bending in accordance with strength design method of the ACI Code. For computing nominal moment capacity (ϕMn), the stem, heel and toe are treated as cantilever beams of unit width and steel area is calculated according to the provisions of the ACI Code. The wall is considered safe against bending if the nominal moment capacity of each component of the wall exceeds the factored maximum moment (Mu) on that component. The expression for computing nominal moment capacity is given as:

$$\phi Mn = \phi A_s f_y \left(d - \frac{a}{2}\right) \tag{2.30}$$

$$a = \frac{A_s f_y}{0.85 f'_c b} \tag{2.31}$$

where

A_s = steel area

f_y = yield strength of steel

f'_c = allowable compressive strength of concrete

d = distance from extreme fiber to the mid of steel

b = unit width

The derivation of above equations can be found in many books on design of reinforced concrete (e.g., McCormac 1986, Hassoun 1985).

2.6.2.6 Checks for Shear

Stirrups are not commonly used in the design of cantilever retaining walls. Therefore, each part of the wall must have enough strength to stand against shear without using shear reinforcement. While making checks for shear, the stem, heel and toe are treated as a cantilever slab (Nilson et al., 1986). The wall is considered safe against shear if nominal shear strength (ϕVc) of each part of the wall is greater than the maximum factored shear (Vu) acting on that part. The expression for computing nominal shear strength of concrete is given as:

$$\phi Vc = 2\phi\sqrt{f'_c}\,bd \qquad (2.32)$$

where ϕ is strength reduction factor and is taken as 0.85 for shear design. f'_c, b and d are same as already defined.

2.7 Soil Properties

The soil properties of the foundation soil and the backfill must be defined for design in order to obtain an efficient and safe design. Lateral earth pressure depends on unit weight and friction angle of backfill. Although, probably stronger, the friction angle of typical clean granular backfill materials used in retaining wall problems is often taken between 30 to 36 degrees and unit weights are often in the range 100 to 115 pcf.

The shear strength and compressibility of foundation soil must be known to design against bearing capacity failures or excessive settlements. The parameters required for the foundation soil are the friction angle, unit weight and cohesion. These parameters can best be estimated using direct shear test since retaining wall is plane strain case. However, these parameters are often inferred from N value of SPT results or from the designer's experience.

CHAPTER 3

EXPERT SYSTEMS AND THE DEVELOPMENT OF TWALL

3.1 Introduction

A brief review of techniques and tools for building an knowledge-based expert system (KBES) or expert system (ES) is presented in this chapter. The application of these techniques and tools to the development of TWALL is also discussed. Some of the recently developed KBES in the domain of geotechical engineering are also described.

Artificial intelligence (AI) is a branch of computer science that deals with the study of how to make computers do things for which, at the moment, people are better (Rich 1983). Expert systems are practical applications of AI research programs involved in problem-solving (Adeli 1988). An expert system can be defined as an interactive computer program incorporating judgment, experience, rules of thumb and intuition to provide knowledgeable advice about various tasks (Gasching et al., 1981).

The reaction of many professionals involved in computer-aided engineering design to the above definition was both uneasiness and impatience. In the opinion of these professionals, present conventional computer programs for engineering applications have become increasingly interactive and perhaps judgment might be best left to the practitioner in this interaction. Fenves (1986) describes the main features of KBES that clearly separate them from algorithmic programs:

1. The knowledge base in KBES can be manipulated independently from the control mechanism.
2. The inference process used in KBES can be conveyed to the user through some form of an explanation facility.
3. To some degree, the domain-dependant knowledge incorporated in the program is readable and understandable.
4. An algorithmic program uses a small amount of knowledge over many cycles, where as KBES typically has to search a large amount of knowledge at each cycle and a particular piece of knowledge may apply only once.
5. The knowledge base can be extended incremently over a period of use without major (or any) restructuring.

3.2 Historical Perspective

In the first 15 years after the birth of artificial intelligence at Dartmouth college in 1956, researchers mostly relied on domain-independent search strategies (e.g., problem reduction, means-end-analysis) to obtain a solution to a problem (Samuel 1963). These search strategies were successful for the solution of some simple or very well structured problems such as games. However, for real complex problems where the search space tend to expand exponentially with the number of parameters involved, these early strategies proved to be inadequate (Rich 1983).

AI researchers then in the early 1970's adopted a new approach that combined the domain knowledge with the problem-solving strategies (Fenves 1986). This marked the first generation of expert systems. As an example, MYCIN, an expert system that diagnoses infectious diseases (Shortliffe 1976) was developed that combined domain specific knowledge and problem-solving strategies.

The second generation of expert systems emphasized knowledge rather than search techniques and lead to the field of knowledge engineering. The problem-solving techniques and the domain-dependent knowledge were separated. This approach permits the combination of new domain knowledge with the existing problem-solving environment (Fenves 1986). Thus, at present the developer of a new expert system has to concentrate on only obtaining, compiling and formalizing the domain-specific knowledge rather than building a problem solving environment (Mullarkey 1985).

3.3 Architecture of an Expert System

The architecture of an expert system refers to the components of the expert system and the way they are connected to each other. The basic components of an expert system are a *knowledge base* (static memory), a *context* (dynamic memory or working memory) and an *inference mechanism*. Additional components including a *knowledge acquisition facility*, an *explanation facility*, a *help facility* and a *user interface* are also needed to enhance the extensibility of an expert system and to make it more user friendly (Adeli 1988). The interrelationship among these components is illustrated in Figure 3.1.

The knowledge base is a collection of facts and heuristics containing information available in a particular domain. The context is a temporary storage facility for the current state of the specific problem being solved and it expands continuously as the reasoning of the solution progresses. The inference mechanism is a control strategy that specifies the order in which the rules will be compared and applied or "fired" in the working memory.

The knowledge acquisition facility provides a means for entering or revising knowledge in the knowledge base. The explanation facility provides reasons why particular questions are being asked and justifies inferences. The help facility guides the user for using the system more effectively. The user interface provides a means for user interaction with the expert system. The interface can be in the form of menus, windows or graphics. A detailed discussion on the architecture of an expert system can be found in Boose (1986) and Nebendahl (1988). The architecture of TWALL

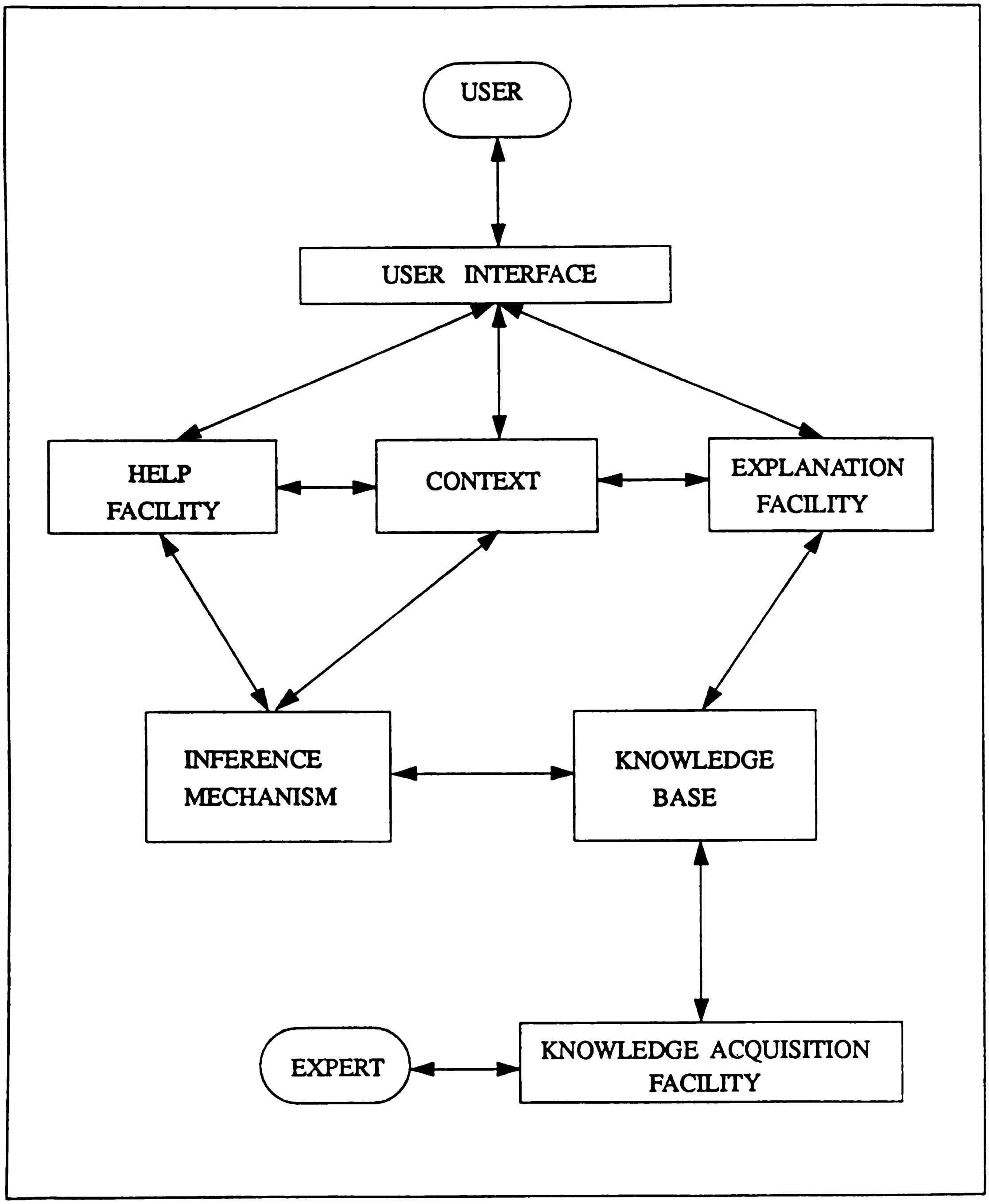


Figure 3.1 Architecture of an expert system essentially contains all the components discussed above and these components are discussed in Section 3.10.

3.4 Knowledge Representation in Expert Systems

The knowledge representation method selected for the domain has a significant impact on the selection of the tool used to build an expert system. Some of the actively used forms of knowledge representation are logic-based representation, rule-based representation and network-based representation (Mullarkey 1987). For detailed discussion on these methods, see Barr et al., (1981), McGee (1990) and Dym et al., (1991)

Most of the developed knowledge-based expert systems are based on the rule-based representation (Adeli 1988). The rule-based systems are also referred to as production systems (Maher et al., 1987). The rule-based systems have an advantage in that they can explain how and why they perform certain action and one can evaluate their outcome and results. The domain knowledge in rule-based systems is represented in the form of "IF...THEN" rules. The general form of the rule is:

```
RULE i
IF [(premise 1).....................(premise n)]
THEN [(conclusion 1 ................(conclusion m]
```

The IF part of the rule is generally referred to as left-hand-side (LHS) while THEN part of the rule is called as right-hand-side (RHS). A single production rule is understood to be a smallest unit of information in the entire system. In contrast to algorithmic programs, an important feature of rule-based KBES is that the rules of the knowledge base need not be in a specified order in which they are to be considered.

3.5 Problem Solving Strategies in Expert Systems

Problem solving generally involves the search for a solution. The solution path consists of all states that lead from the initial state to the goal state (Maher et al., 1986). Problem solving strategies (also referred to as control strategies or inference mechanisms) commonly used in rule-based systems are: forward chaining, backward chaining and the hybrid approach (Adeli 1988). In these strategies, the goal state represents a potential solution and the initial solution state represents the input data. These strategies are currently implemented in a variety of rule-based expert system building tools commercially available in the market (e.g., LEVEL5, M.1 and Ist-CLASS)

3.5.1 Forward chaining

Forward chaining strategy (also referred to as bottom-up, data driven or antecedent driven) is a problem-solving strategy that starts from an initial state of known facts and proceeds forward to infer their immediate conclusion. The conclusions are added to known facts in the context and further inferences are made. This process continues until the goal state is achieved or no useable rule is found. This strategy is useful where there are few input data and many solutions (Maher et al., 1987). As an example, DIPMETER ADVISOR (Davis et al., 1981) uses forward chaining control strategy for inferring subsurface geological structure.

3.5.2 Backward Chaining

Backward chaining is a problem-solving strategy that starts with the goal of the problem and works backwards, looking for evidence that supports or contradicts the goal. The process involves looking at the THEN part (conclusion) of the rules that would conclude the goal and then examining the IF parts (premises) of these rules to determine what situation will cause them to fire. Backward chaining is also referred to as goal-driven, antecedent driven or top-down strategy. This strategy is suitable where there is large input data and few goals. Backward chaining is often employed in diagnostic problems such as MYCIN (Shortliffe 1976) for diagnosing infectious diseases and WASTE INCINERATION (Huang et al., 1986) for diagnosing malfunction in hazardous waste incineration facilities.

3.5.3 Hybrid Approach

The hybrid approach is a combination of backward chaining and forward chaining. This approach utilizes a "blackboard" environment. The blackboard will keep track of the simultaneous application of forward and backward reasoning chains (Adeli 1988). A good discussion on use of the blackboard model for problem-solving is given by (Nii 1986). The LEVEL5 expert system shell (LEVEL5, 1989) can be used to develop expert systems using hybrid approach.

3.6 Expert System Building Tools

Basically, there are three types of tools available for building KBES (Hayes-Roth et al., 1983, Harmon and King 1985, Mullarkey 1987): general-purpose programming languages (GPPL) such as LISP and PROLOG, general-purpose representation languages (GPRL) such as OPS83 (Adeli 1988) and expert system building frameworks or shells (e.g., LEVEL5). These tools are briefly discussed as below:

3.6.1 General-Purpose Programming Languages

Presently, KBES can be implemented in AI languages such as LISP and PROLOG as well as in procedural languages such as C and PASCAL (Adeli 1988). LISP is an acronym for LISt Processing. It was invented by McCarty in 1960 for nonnumeric computations (Adeli 1988). This language is the choice of many AI researchers in United States and is most suitable for symbolic representation and list processing (Harmon and King 1985).

PROLOG is an acronym for PROgramming in LOGics. It is based on formal logic and a simplified version of first-order predicate logic (Clocksin et al., 1981). PROLOG is popular in Europe and Japan (Nebendahl 1988). It is a versatile language for database type applications but has limitations for numeric data manipulation (Adeli 1988).

The development of many engineering KBES involves a considerable number of algorithmic computations in addition to symbolic manipulations. Therefore, AI languages may not be preferred for engineering applications. Among the popular algorithmic languages, PASCAL and C might be better candidates in these cases (Adeli 1988).

System developers that use general programming languages as a tool to build KBES have complete flexibility in designing the system but they have to implement the entire structure including the knowledge base, inference mechanism and other components of the system. The cost of this approach is very high in term of time and efforts. This approach is suitable for those interested in more basic issues of expert system building techniques (Mullarkey 1987). An important approach that is becoming increasingly popular for developing new expert systems is the use of "shells" to be described in 3.6.4.

a

t

r

ea

19

dr

3.6

ic p

3.6.2 General-Purpose Representation Languages

These languages are generally classified by the form in which the knowledge base is represented e.g., as a production system (Newell 1977) or as a frame-based system (Stefik 1979). These tools such as OPS83 (Adeli 1988), UNIT (Stefik 1979) provide maximum flexibility to the developer in designing a system for a specific application. The difficulty with these tools is that a significant portion of the code necessary to produce a working KBES must be written and manipulated by the program developer (Mullarkey 1987).

3.6.3 Expert System Shells

Expert system shells, also referred to as frameworks and environments, have been recently developed to facilitate the development of KBES. These are expert systems without the knowledge base and usually provide one or more knowledge representation methods and inference mechanisms. They are easier to use but less flexible than an GPPL and GPRL (Adeli 1988). There are two main categories of these shells; domain driven-shells and domain-independent shells (Mullarkey 87).

3.6.3.1 Domain-Specific Shells

Domain-specific shells are those developed from specific parent expert systems by separating knowledge base from the control mechanism. They can only deal with same class of problem as the original system because of control strategy incorporated in the inference mechanism. These tools are developed for either diagonistic tasks such as EMYCIN (vanMelle 1979) and EXPERT (Weiss et al., 1979) or interpretation tasks such as HEARSAY (Balzer et al., 1980). These tools are not suitable for problems involving extensive mathematical computations.

3.6.3.2 Domain-Independent Shells

Domain independent shells are those developed independently of a application domain. Usually, multiple forms of knowledge representation and control strategies are available in these shells (Mullarkey 1987). The KBES developer chooses the type of knowledge representation and control mechanism and adds domain-specific knowledge within the constraints imposed by the particular representation.

Expert system building shells are ideal tools for developing KBES for those not expert in computer science. Incorporation of the rules in such a package is far simpler than building a complete system including an inference mechanism. Few civil engineering problems can be solved by a purely heuristic approach. Numerical algorithmic routines must usually be combined with heuristics (Kostem 1986). Thus, an ES shell for civil engineering application should be able to handle scientific numerical computations within the system. The ideal tools for building KBES in civil engineering applications would allow for the following (Ludvigsen et al., 1986, Adeli 1988):

1. Extensive mathematical manipulation within the system.
2. Different forms of knowledge representations.
3. Various control strategies.
4. Interfacing ability with other programs written in any languages.
5. Natural language interface.
6. Explanation of static queries of knowledge and dynamic queries about the line of reasoning.
7. Programming aid (e.g., editor and debugger).
8. Reasonable Cost.

ES shells available in the market at the time of this effort have been analyzed in some detail by Ludvigsen 1986, Mullarkey 1987 and Adeli 1988. Table 3.1 shows the comparative capabilities of PC-based expert system shells. Only PC-Based shells are considered because the developed system is expected to be used on personal computers which are easily accessible. The LEVEL5 expert system shell (LEVEL5 1989) met all criteria discussed above except that it allows only one form of knowledge representation i.e., rule-based representation. The characteristics of LEVEL5 are discussed briefly as follows:

LEVEL5 is an "advanced development environment and

Table 3.1 Comparison of PC-Based expert system shells (Modified from Ludvigsen et al., 1986)

ATTRIBUTE	EXPERT-EASE	LEVEL5	M.1	Ist-CLASS
Proprietary interest	Human Edge Software	LEVEL5 Research Inc.	Teknowledge	
List price (1987)	$695 (IBM-PC)	$ 495 (IBM-PC)	$ 5000 (IBM-PC)	$495 (IBM-PC)
Ability to handle complex math	NO	YES Directly	YES Indirectly	YES Indirectly
Ability to interface with other software	NO	YES Directly	YES Directly	YES directly
Explanation	NONE	Extensive	Limited	NONE
Overall friendliness	Buddies	A Friend	A Friend	A Friend
Documentation	Outstanding	Sufficient	Sufficient	Limited
User Support	Limited	Available	Available	Available
Inference mechanism	Forward Chaining	Forward and Backward Chaining	Backward and Limited Forward Chaining	Backward and Forward Chaining

delivery vehicle for expert system" (LEVEL5 1989). It was developed by Level Five Research in PASCAL in 1986 and uses a ruled-based knowledge representation. LEVEL5 can handle complex mathematical tasks and uses both backward chaining and forward chaining control strategies.

LEVEL5 is entirely menu and function key driven and is easy to use. It allows easy integration with algorithmic programs written in TURBO PASCAL, FORTRAN and C or any other program that is a .BAT, .COM or .EXE file. It also permits installation of up to three external programs on its main menu that can be run form within LEVEL5. The ACTIVATE facility of LEVEL5 can execute dBASE-II programs from within LEVEL5.

Its facilities include a help facility, explanation facility and text editor. LEVEL5 has the capability to explain both the static queries of knowledge and dynamic queries about the line of reasoning. LEVEL5 can be used on an IBM PC with as little as 256 K of RAM. However, to use all its features, 512 K RAM is required. The knowledge bases of LEVEL5 can be chained and compiled. It has the ability to address 4000 rules and is available at relatively modest price. Looking at the price and the capabilities, LEVEL5 seemed to be one of the best commercial ES shells available in the market for developing engineering KBES on microcomputers (Adeli 1988) and was selected for the development of TWALL.

3.7 Previous Geotechnical Applications

Some previous applications of expert system technology to geotechnical engineering problems are briefly described in the following sections.

3.7.1 RETWALL

RETWALL (Hutchinson et al., 1987) is an expert system for selecting and sizing earth retaining walls. RETWALL was implemented on SUN2 Microsystems using the expert system shell BUILD, a backward-chaining production rule system. The system also employs graphical procedures written in C. The user interface is through multiple windows and graphics. RETWALL provides extensive explanations in the form of 'Why', 'note list' and 'explain' predicates.

The knowledge-base of RETWALL contains knowledge of various prototype retaining wall cross sections and how to select among them. This knowledge is not well documented in literature so it was obtained from specialist engineers in the field through survey. The selection of the most appropriate type of retaining wall is based on type of application, soil and topographical conditions and designer preferences.

The system has two main modules, the high level and low level. The purpose of high level is the selection of the particular retaining structure for a given application. At present, the system can choose among 10 available wall types. The lower level module is designed to perform the preliminary design of the selected retaining structure. Presently, the only lower level routine available is that which designs blockwork walls.

3.7.2 CONE

CONE (Mullarkey 1985) is a knowledge-based system that classifies soils based on cone penetrometer data and infers shear strength of the soil. The knowledge incorporated into CONE is embodied in a series of production rules using the OPS5 programming language and LISP functions.

The knowledge base of CONE consists of three main modules: information gathering, soil classification and shear strength estimation. Both backward and forward chaining control strategies are used in CONE. The information gathering process uses backward chaining strategy and the soil classification and shear strength estimation uses a forward chaining strategy. CONE uses fuzzy logic to represent the uncertainty in the empirical interpretation of the data.

3.7.3 RETAIN

RETAIN (Adams et al., 1988 and Adam et., al 1990) is a KBES for retaining wall failure diagnosis and rehabilitation design synthesis. RETAIN consists of a database implemented in DBMS INFORMIX and series of modules including site identification, failure diagnosis, design synthesis, cost estimation and evaluate/consistency. The database integrates OPS83 production rules, C language algorithmic functions and INFORMIX ESQL database queries. The RETAIN system uses DIGR inference engine to traverse the network. RETAIN system was developed on a Microwaves workstation but the entire system has also been transported to a PC.

The knowledge base for retaining wall failure diagnosis contains possible failure modes of all possible wall types as well as possible evidence associated with each failure mode. The heuristic knowledge base for design synthesis is represented as relational database tables. For problem-solving, the RETAIN system uses the derivation approach for retaining wall failure diagnosis and the formation approach for the synthesis of rehabilitation design (In the derivation approach, a solution of the problem at hand is derived from a list of predefined solution stored in the knowledge base; In the formation approach, a solution is formed from the eligible solution components stored in the knowledge base).

3.8 Background on Present Research

Numerous procedural computer programs have been used in the past for the design of cantilever retaining walls.

Newman (1976) used a procedural program to produce a structural design of cantilever wall for various loading conditions and heights. A computer program was used by Rhomberg and Street (1981) to compile a design aid for concrete cantilever retaining wall design within 5% of absolute minimum cost. The U.S. Army Corps of Engineers (U.S. Army, 1989) makes extensive use of computer programs for the design of retaining structures.

In these programs, most if not all of the decision-making process is left to the user or alternatively, procedural programs (e.g., TWDA by Price et al., 1980) use numerous iterations for optimum design. In addition, they have a limited knowledge base and can't explain their working and justify their answers. Recently developed knowledge-based expert systems have overcome some of the limitations of procedural programs. The main characteristics of KBES are discussed in section 3.1 and these include the separation of knowledge base from the control mechanism, use of heuristic knowledge and the explanation facility.

An extensive literature review revealed that no attempt has been made to develop KBES for the structural design of cantilever retaining walls. Thus, the decision was made to develop a system for the design of cantilever walls that would guide the user through iterative design process by using heuristic rules incorporated in the knowledge base. The other aspects of cantilever retaining wall design that were investigated are: (1) a comprehensive parametric sensitivity analysis was made to understand the behavior of the wall under different loading conditions, develop heuristics and test the program and (2) a study was made to see the effect of active and at-rest conditions on the cost of the wall.

3.9 Development of TWALL

3.9.1 General

Traditionally, a knowledge engineer, (AI specialist) cooperates with a team of domain experts (specialists of a particular domain) for developing a KBES. Since the human experts may not be knowledgeable about KBES programming, the knowledge engineer translates the expert's knowledge into the system. With the recent invention of expert system building shells, the domain expert can also act as knowledge engineer with a little programming background. The knowledge engineer must first acquaint himself or herself with the application domain and then obtain domain experts's knowledge through interviews, literature, experimentation and questionnaires. For techniques of knowledge elicitation, see Greewell (1988) and Cordingely (1989).

Some of the basic steps involved in the development of an expert system include problem identification, analysis and acquisition of knowledge, selection of expert system building tool and inference mechanism and formalization of the knowledge base. The next step is to develop a prototype system using the knowledge base and AI techniques. The subsequent step is the evaluation, review and expansion of the developed system, refinement of the user interface and the addition of user facilities. For a detailed discussion see Harmoon and King (1985) and Kulikowski (1989).

The knowledge-based expert system TWALL for the design of cantilever retaining walls was developed as follows:

1. Preliminary design tasks were performed after reviewing the literature on the design of cantilever walls and expert systems. These included problem identification, problem conceptualization, selection of expert system building tool, method of knowledge representation and inference mechanism.
2. A prototype knowledge-based system was developed based on knowledge obtained from the literature for proportioning wall dimensions to ensure internal and external wall stability. Some heuristics were developed by running the program with different wall dimensions and observing their effect on wall stability i.e., simulation and experimentation. See Chapter 4 for details.
3. Parametric sensitivity analysis was performed by varying input variables that affect wall design within a practical range and computing the safety factor against overturning, sliding and bearing capacity failures. The analysis was also performed to see the effect of change

in heel length on upward soil pressure beneath the base under different loading conditions. The analyses are discussed in detail in Chapter 5. Some heuristics were deduced from this analysis for incorporating in the system during its expansion.

4. The effect of active and at-rest conditions on the cost of the wall was studied (see Chapter 6).

5. A questionnaire was sent to experts associated with the design of retaining walls to further define heuristic knowledge. Some of the previous heuristics were revised. A specimen questionnaire is shown in Appendix A. The knowledge obtained form the experts and the development of heuristic are discussed in Chapter 7.

6. The developed prototype was expanded by incorporating heuristics deduced from previous work.

The major stages of TWALL development are discussed in detail in the following sections.

3.9.2 Problem Identification

Identification of an appropriate problem is an extremely important first step in developing an expert system. There are several guidelines that can help to determine whether a certain task is appropriate as a basis for KBES development. Some of the yardsticks of a good domain are (Fenves et al., 1984, Mullarkey 1985 and Prerau 1989):

1. The use of expert knowledge, judgement and experience is the key element in the performance of the task being considered.
2. There is a need for non-conventional programming approach.
3. The task is decomposable and the development of the expert system can be phased.
4. Major components of the domain knowledge are available from books and publications.
5. Domain experts are available and can be debriefed for heuristic knowledge.
6. It takes several hours to several days for an expert to complete a typical task.
7. Basic skills required for the task are routinely taught to the novices but expertise is gained through experience.
8. The need for the task is expected to continue for several years.

3.9.2.1 TWALL Implementation

The domain characteristics of cantilever retaining walls design are discussed below in the context of the eight criteria above to see whether the domain is suitable for using expert system technology:

1. The design values of shear strength parameters of

backfill and foundation soil that are used for the wall design are not reliable. The uncertainty is due to random variability of properties and insufficient sampling. The value of wall friction angle to be used in the design is also highly uncertain. Intuition, judgement and previous experience have to be used to select right value of design parameters. Heuristic rules deduced from designers experienced in the wall design can be incorporated in the expert system to guide novice users.

The design of a cantilever wall itself is a trial and error procedure. To reduce the number of trials and computational time, the designer is required to assume reasonable trial dimensions (e.g., base length, heel length, and stem thickness). Further experience is necessary regarding how to change the trial design based on the results of one iteration of analysis. Novice users can be guided through heuristics incorporated in an expert system.

2. The design of a cantilever wall requires both symbolic reasoning and numerical calculations. Thus, a non-conventional approach is desirable.
3. The task of cantilever retaining wall design can be decomposed in to sub-tasks such as external stability and external stability and so on. Also, the expert system can be developed in phases according to the sub-tasks.
4. The major components of the domain knowledge of the

wall design are available form books, journals and publications.

5. There is a need to capture expertise from the experts on the wall design and experts are available from whom the heuristic knowledge can be obtained.
6. Wall design is a time consuming job and may take many hours to complete the design.
7. The design procedures of cantilever retaining wall are routinely taught but expertise is only gained after a considerable experience.
8. Cantilever retaining walls are being used to retain soil and their use is expected to continue in future for long time to come.

From the above discussion, it is evident that the design of cantilever walls is an appropriate domain for using expert system technology.

3.9.3 Collection of Knowledge

The domain knowledge of a cantilever wall design consists of heuristic knowledge and descriptive knowledge. The heuristic knowledge expresses surface relationships which an expert has observed to be of some use when tackling problems in the domain. The descriptive knowledge represents the formally expressed laws and relationships which make up the theory of problem domain (McGee 1990).

There are two main sources of knowledge; literature and human experts. The descriptive knowledge for the design of cantilever wall was mostly obtained for books, journals, specifications and magazines. However, these sources lack heuristic knowledge. To obtained heuristic knowledge, a questionnaire was sent to several experts associated with the design of retaining walls. See Chapter 7 for discussion on knowledge obtained from the experts.

Dr. Thomas F. Wolff (Associate Professor, Michigan State University) has been involved in design and construction of retaining structures, revision of design manuals and the development of computer programs for retaining walls during his long association with the U.S. Army Corps of Engineers. He acted as domain expert throughout the development of TWALL and was consulted as and when required.

3.9.4 Problem Conceptualization

In this phase of knowledge base development, an initial study of the problem is carried out to define the goal and identify the key concepts and relationships that form the basis for expert's decision (McGee 1990). The problem is decomposed into sub-problems until the knowledge engineer has produced a complete top-down hierarchical view of the problem-solving process. Clear distinctions are also made between evidence and hypothesis and action to be taken at each step is carefully specified (Kulikowski 1989).

In this phase of TWALL development, the goal and sub-goals were defined and key concepts and relationships were identified for making various decisions. As an example, the main goal in the present case is "safe cantilever wall design" and sub-goals are "external stability and internal stability". The problem was decomposed into sub-problems and a complete top-down hierarchical view of the problem-solving process was produced as shown in Figure 3.2. The figure reads from left to right.

3.9.5 Selection of Expert System Building Tool

Artificial intelligence (AI) languages such as LISP and PROLOG offer definite advantage over procedural languages (e.g., PASCAL, FORTRAN and BASIC) with regard to representing heuristic knowledge. But these languages have limitations for descriptive knowledge that needs extensive numeric data manipulation. AI languages are also considered memory intensive and slow as compared to procedural languages.

The KBES for the design of a cantilever walls could have been developed using one of the following approaches.

1. The heuristic knowledge could be coded in LISP or PROLOG and the descriptive knowledge could be coded in some high level language (e.g., PASCAL and FORTRAN). An interface would then be developed to maintain the integrated environment.

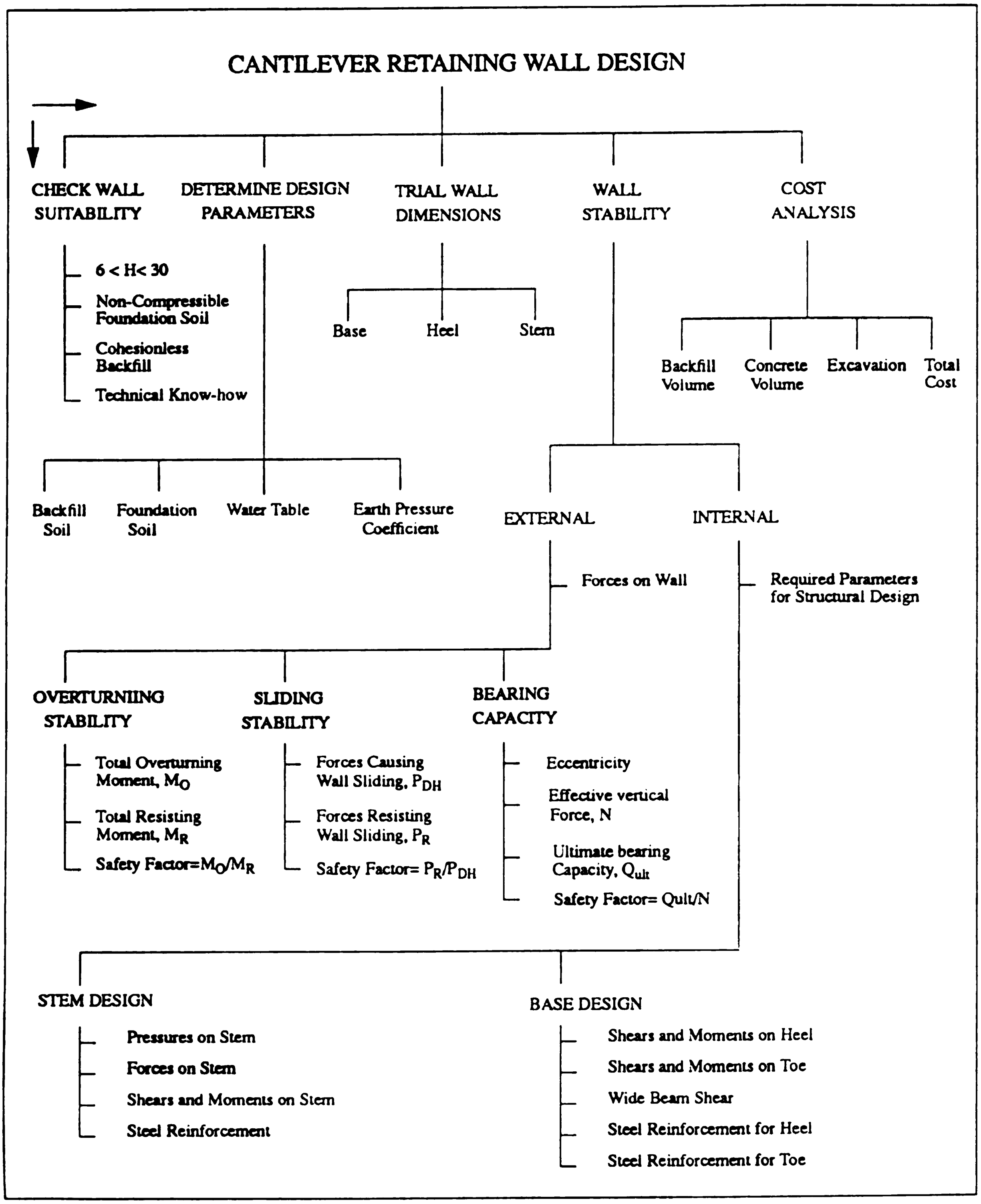


Figure 3.2 Hierarchy of cantilever retaining walls design

2. A complete system could be developed in some procedural language such as PASCAL which is fairly good at symbolic reasoning as well as numeric data manipulation.
3. A commercially available expert system building environments or shells could be used to develop a new system.

Building a KBES using the first two approaches amounts to building a complete system including inference mechanism, explanation facility, help facility and knowledge acquisition facility. The development of these facilities is a specialist job and mostly performed by AI specialists. In addition, the AI languages are not compatible with other languages (Finn et al., 1986) and the development of an interface is tedious. To build a complete system demands enormous time and efforts and may take five to ten man years to build such a system (Fenves et al., 1984). Also, due to availability of expert system building environments in the market, building a complete system is not innovative except for those involved in AI research.

The invention of expert system shells has facilitated the development of KBES. Here, a builder of new KBES is required to select the type of knowledge representation, inference mechanism and add the domain-specific knowledge into the existing framework within constraints imposed by a selected representation. Presently, it is not very difficult to find suitable shell for a given domain.

3.9.5.1 TWALL Implementation

The third approach as discussed above was followed for the development of TWALL. The LEVEL5 expert system shell developed by Information Builders (LEVEL5 1989) was selected for the present application because it meets all the requirements to develop a KBES for the design of cantilever retaining walls.

3.9.6 Knowledge Representation

Methods of knowledge representation in expert systems were briefly discussed in section 3.4. The framework of organizing information and knowledge into a knowledge base of TWALL is provided by a knowledge engineering language known as Production Rule Language (PRL). PRL is a versatile environment for the formulation of an expert's knowledge into LEVEL5 expert system shell with a wide range of data types and functions. PRL knowledge bases are compiled before being executed and take less memory and time than symbolic languages-based systems. They allow development of sophisticated and interactive program in much less time and with much less effort than the conventional programming languages.

The production rule is used as basic construct of knowledge representation in PRL knowledge base. Ordering of rules within the knowledge base is not important and new rules can be added any time. PRL is capable of representing several different types of information in a single knowledge base including simple factual statements, numeric data, mathematical expressions, attribute-value associations and strings.

A simple fact data type is defined as any phrase or statement which can be asserted to be either true or false. A numeric fact is a fact with numeric value. PRL supports integers and floating point decimal as numeric data. PRL also supports assignment, basic algebraic operations and exponential and trigonometric expressions. Attribute-value facts represent objects with common states or conditions. The string fact type can be any combination of ASCII characters with a maximum length of 80 characters.

3.9.7 Selection of Control Strategy

Control strategies in expert system were discussed in section 3.5. The LEVEL5 expert system shell has both backward and forward chaining control strategies. Basically, the inference engine of LEVEL5 follows backward chaining control strategy by default but forward chaining can also be simulated. For the present design, the backward chaining control strategy was followed because it is was found convenient to follow this strategy in LEVEL5.

Backward chaining control strategy is considered appropriate for diagnostic type problems instead of design problems (Adeli 1988). For the design of cantilever walls, the knowledge base was structured such that the use of backward chaining control strategy did not pose any problem. It shows that the backward chaining can be used for design problems with carefully structured knowledge base.

3.9.8 Knowledge Formalization

In this phase, the concepts and relations identified in the conceptualization phase are mapped onto the formal representation which can be interpreted by the computer program (McGee 1990). If the expert system building tool has already been selected, the purpose of this phase is to find an appropriate mapping from a semi-formal domain knowledge into a formal representation mechanism provided by the tool. Else, the formalization phase can provide a valuable input for the selection of an appropriate tool for building the expert system. For the development of TWALL, the concepts and relations identified in the conceptualization stage were mapped on to PRL provided by LEVEL5.

3.9.9 Prototype Implementation

The prototype knowledge base is built up in this phase. The ES builder must select the scope of sub-programs to be covered by the prototype. Once the sub-programs have been formalized and represented within the chosen building tool, the changes in the formalization will inevitably appear. Thus, the conceptualized and formalized knowledge is modified to build a working prototype (Kulikowski 1989). The knowledge for the prototype is mostly obtained from the published literature on the subject (Fenves et al., 1984).

3.9.9.1 TWALL Implementation

A prototype working knowledge base was developed in this phase of TWALL development. Formalized knowledge was compiled using the LEVEL5 compiler and modifications and corrections were made in the formalized knowledge to build a working prototype. The knowledge for the prototype was obtained mostly from the literature.

3.9.10 Testing, Validation and Expansion

In this phase, the developed prototype is tested for programming errors and validated for the intended tasks. According to the test results, the knowledge base is modified and expanded by incorporating heuristic knowledge obtained from the domain experts.

3.9.10.1 TWALL Implementation

The developed prototype was tested for any bugs in the program and validated for the reliability of results. For validation, two approaches were used; comparison to student designs and comparison to published designs. In the first approach, a problem of cantilever retaining wall design with different design parameter was given to students in an advanced foundation design course (CE 818) at MSU and the class was asked to design the wall using the developed prototype and check the results manually. Also, the students in an earth retaining structure design course (CE 419) were asked to design cantilever walls for 34 different sets of parameters and then these 34 walls were designed on TWALL for comparison. In the second approach, examples on cantilever walls design in different text books and design manuals were solved using the developed prototype and results were compared.

The results of first approach compared well. However, there were slight differences and the system was modified accordingly. The system was also modified to improve the user interface as suggested by the CE 818 Class. Appendix D shows the comparison of TWALL designs with that of CE 419 Class. The results of the second approach are shown in Table 3.2 and 3.3. TWALL output is given in appendix B.

Table 3.2 shows the comparison of TWALL wall results with Example 1, Appendix N, The US Corps of Engineers Manual (EM 1110-2- 2502). The results of external stability compare fairly well but there are significant differences in internal stability results. The reasons for this difference are:

Table 3.2 Comparison of TWALL results with Exapmle 1, Appendix N, The US Army Corps of Engineers Manual (EM 1110-2-2502 1989).

ITEM		TWALL	Corps of Engineers (1989)	Percent Difference
Wall Dimensions				
Wall heigth	ft	25.00	25.00	0.00
Base length	ft	18.78	20.00	-6.49
Base Thickness	ft	3.00	3.00	0.00
Heel length	ft	9.62	12.00	-24.70
Toe length	ft	6.67	5.00	25.03
Stem top thickness	ft	1.50	1.50	0.00
Stem bottom thickness	ft	2.49	3.00	-20.48
Earth Pressure				
Method for earth pressure prediction		Jaky (at-rest)	General wedge	
Earth pressure coefficient K		0.561	0.547	2.49
Earth force on stem	kips	16.29	24.06	-47.70
Earth force on wall	kips	26.79	27.62	-3.09
Wall Stability				
Overturning stability				
Xr	ft	8.61	7.34	14.75
Eccentricity	ft	0.78	2.66	-241.00
B/6	ft	3.13	3.33	6.38
Safety factor		2.83	2.43	14.13
Sliding safety factor		1.68	1.71	-1.78
Bearing safety factor		8.08	6.38	21.03
Structural Design				
Steel for stem	(sq-in/ft)			
Top of Stem		0.58	-	-
Middle of Stem		0.82	-	-
Bottom of Stem		1.96	3.14	-60.20
Steel for heel	(sq-in/ft)	1.88	3.13	-66.49
Steel for toe	(sq-in/ft)	1.30	0.90	30.77

Table 3.3 Comparison of TWALL results with Example 12.4 Bowles (1982)

ITEM	TWALL	BOWLES (1982)	Percent Difference
Wall Dimensions			
Wall heigth ft	28.40	28.40	0.00
Base length ft	14.64	14.42	1.50
Base thickness ft	2.42	2.42	0.00
Heel length ft	9.00	9.50	-5.50
Toe length ft	3.74	3.00	19.78
Stem top thickness ft	1.25	1.30	-4.00
Stem bottom thickness ft	1.89	1.92	-1.58
Earth Pressure			
Method for earth pressure prediction	Coulomb	Rankine	
Earth pressure coefficient K	($\delta=\beta$)		
Earth force on stem kips	0.294	0.294	0.00
Earth force on wall kips	11.42	11.43	0.08
	15.22	15.33	-0.72
Wall Stability			
Overturning safety factor	2.60	2.54	2.30
Sliding safety factor			
Considering passive pressure	-	2.45	-
Neglecting passive pressure	2.02	2.05	-1.49
Bearing capacity			
Eccentricity ft	1.59	1.84	-15.72
Safety factor	5.17	4.30	16.82
Structural Design			
Steel for stem (sq-in/ft)			
Top of Stem	0.46	0.50	-8.68
Middle of Stem	0.61	0.64	-4.91
Bottom of Stem	2.30	2.26	1.73
Steel for heel (sq-in/ft)	1.62	1.81	-11.73
Steel for toe (sq-in/ft)	1.02	1.02	0.00

1. For the structural design of the stem, the Corps considers a section at the end of heel for computing earth force on stem which is justified only if the surface of the top of the heel is perfectly smooth. In reality, the top heel surface is rough and taking section at the end of the heel with sloping backfill results in very high earth force on the stem.
2. For the structural design of the heel, the Corps uses a longer heel than TWALL that results in large moments at the intersection of heel and stem. Consequently, the requirement of steel for Corps design is more than the TWALL.
3. For the toe design, TWALL uses a longer toe than the Corps. Therefore, required steel for TWALL design is more than the Corps design but its overall effect would be insignificant because toe length is much shorter than the heel length.

In summary, the Corps design seems to be conservative because the Corps assumed a section at the end of the heel for computing earth force on the stem that resulted in very high earth force on stem. TWALL results compared very closely with Bowles, Example 12.4 (Bowles 1982) as shown in Table 3.3

In this phase of TWALL development, the developed prototype was also expanded by incorporating the heuristic rules. These heuristic rules were derived from literature review, parametric sensitivity analysis, simulation and experimentation and knowledge obtained from the experts on wall design (see chapter 4 for detailed discussion).

3.10 Architecture of TWALL

A schematic representation of TWALL is shown in Figure 3.3. The various components of TWALL are described briefly in the following sections.

3.10.1 Knowledge base

The knowledge base of TWALL consists of the domain-specific knowledge and the control knowledge. The domain specific knowledge consists of goal statements and production rules. The control knowledge consists of procedural rules and control commands (e.g., DISPLAY, FORGET CYCLE). There are a total of 297 rules in the knowledge base of TWALL. The knowledge base of TWALL is discussed in detail in Chapter 4.

3.10.1.1 Goal Statements

The goal statements are simple or object attribute facts which describe a conclusion that can be reached by the knowledge base. For each goal statement there should be at least one rule in the knowledge base that has the same

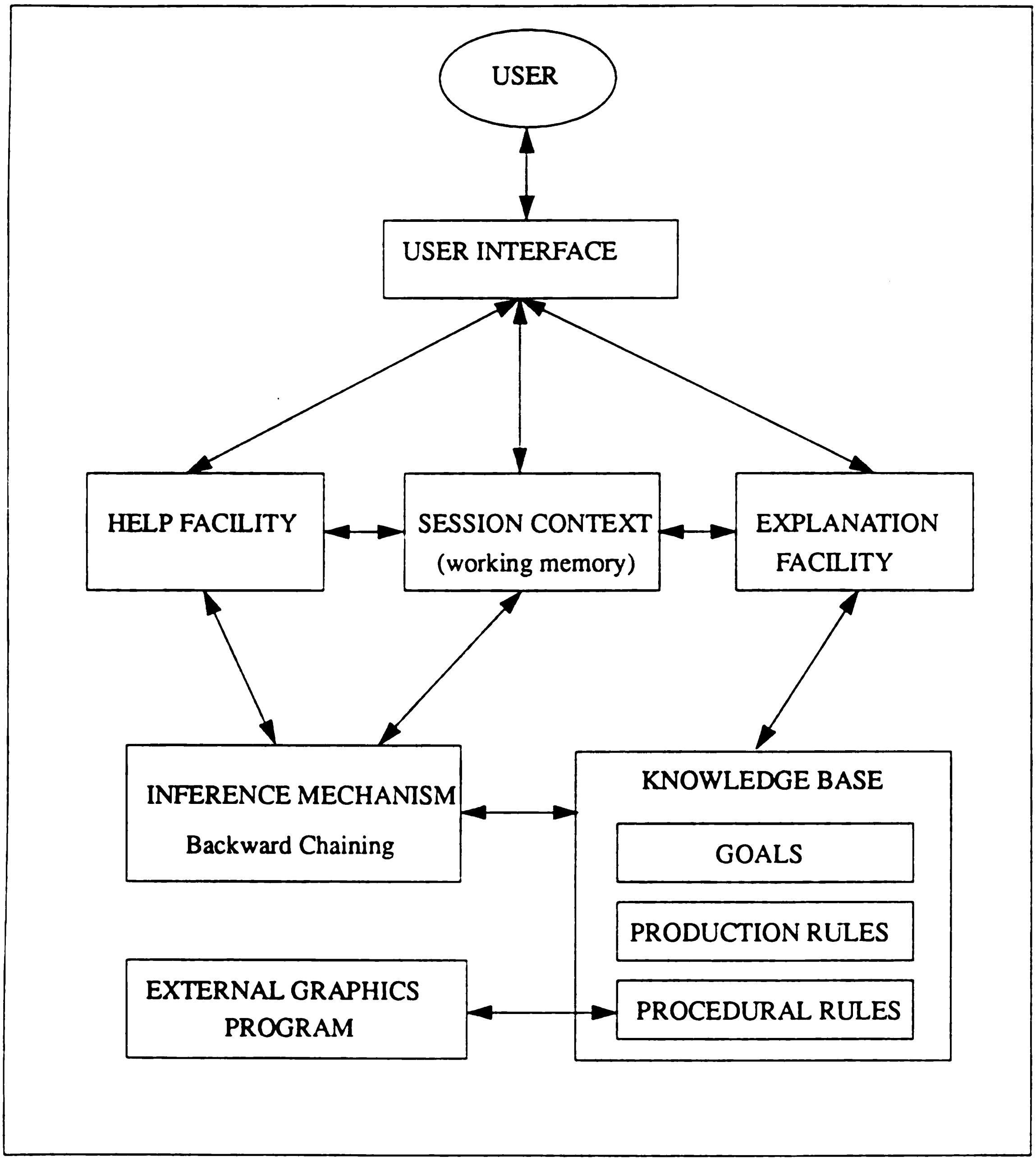


Figure 3.3 Architucture of TWALL

conclusion as that of the goal statement. Each goal statement must be preceded by a goal number. As an example, one of the goal statement used in TWALL is:

2.1 Cantilever wall design is safe

3.10.1.2 Production Rules

A production rule is a basic building block of the knowledge base and consists of a rule statement, premise and a conclusion. The rule statement is a name given to the rule; it can be a simple fact or a string. The premise part of the production rule consists of IF, AND, and OR statements and the conclusion part consists of THEN, AND and ELSE statements. If all statements of premise part are TRUE, then the state of the fact of the THEN statement is added to session context. The ELSE statement is invoked only when the premise part of the rule is FALSE. An example of a production rule used in TWALL is:

```
RULE  wall suitability
IF    wall suitability1
OR    user preference
THEN  cantilever wall suitable for present application
ELSE  cantilever wall is unsuitable
AND   DISPLAY wall unsuitable
AND   FORGET ALL
AND   CYCLE
```

3.10.1.3 Procedural Rules

The main function of the procedural rules is to interact with an external programs. The procedural rule can be used to read data from the disk file or write data on an external device. They can also be used to activate the external programs. An example of a procedural rule used in TWALL to call an external graphics program and to pass parameters through a disk file is:

```
RULE  activate
ACTIVATE GTWALL.EXE
DISK  GDATA.PRL
SEND  H
SEND  HS
SEND  B
SEND  tb
SEND  heel
SEND  toe
THEN know activate external program
```

3.10.2 Inference Mechanism

The inference mechanism in TWALL follows backward chaining control strategy as already discussed in section 3.9.7.

3.10.3 Session Context (working memory)

The session context is a scratch pad where facts obtained during consultation session are stored in the memory. The current value of any fact of the context of the session can be incorporated into a TEXT, DISPLAY or EXPAND displays. See the LEVEL5 user manual for more details (LEVEL5 1989).

3.10.4 User Interface

The communication between the user and TWALL is through the keyboard and CRT screen. Input data for wall design are provided by the user either by giving appropriate values of the design parameters or answering the queries made by TWALL. The values calculated by rules in TWALL can be changed at any time using CHNG and RUN function keys provided by LEVEL5. The help facility in LEVEL5 is a context-sensitive on-line help system that is available from most points within the system. The information about all aspects of LEVEL5 can be obtained after entering the help system.

3.10.5 Explanation Facility

TWALL assists the user to respond to the queries by providing various explanations. As an example, TWALL renders the following explanation of embedment depth when the user fails to understand the query about embedment depth.

EMBEDMENT DEPTH

A vertical distance to which the base in front of a retaining wall is laid below ground surface is called embedment depth. The base should be placed below the depth of frost action, zone of seasonal variation and depth of scour. The embedment depth may not exceed half the base length so that the assumption of shallow foundation is not violated.

The explanation facility of LEVEL5 is through the "report" system. The user can enter the system by pressing the "WHY" function key. The information about reasoning process can be obtained through four menus:

1. Using the Fact Menu, the user can see the answer to the question and conclusions drawn or can change, add or delete the facts.
2. From the Rule Menu, the user can review the rules of the knowledge base and trace the line of reasoning.
3. From the Option Menu, the user can save or retrieve the context of the knowledge base.
4. From the Report Menu, the user can generate the knowledge tree showing the logical sequence of rule fired.

3.10.6 External Graphics Program

An external graphics program called GTWALL was coded in Microsoft FORTRAN to draw the final design sketch of the wall. The design parameters are passed from the expert system to GTWALL through a disk file. After displaying the design sketch, the external program returns the control back to the expert system.

CHAPTER 4

TWALL: KNOWLEDGE BASE

4.1 General

The knowledge base of TWALL is developed in Production Rule Language PRL (i.e., IF, THEN, ELSE type rules). There are a total of 297 rules used in the development of this knowledge base. The rules are further classified into 14 building blocks (BB's) as shown in Figure 4.1. The main idea of using BB's is to classify all the required rules according to their intended uses. For example, rules that check the suitability of a cantilever retaining wall for a given application can represent a building block. The division of knowledge base into building blocks has also helped to understand and explain the key concepts and relations used in the development of the knowledge base.

The control knowledge needed for solving a problem is developed in BB's and is represented by means of control commands. For example, the SEND command can be used to pass parameters to an external program through a disk file. A building block may be executed once or many times depending upon its function.

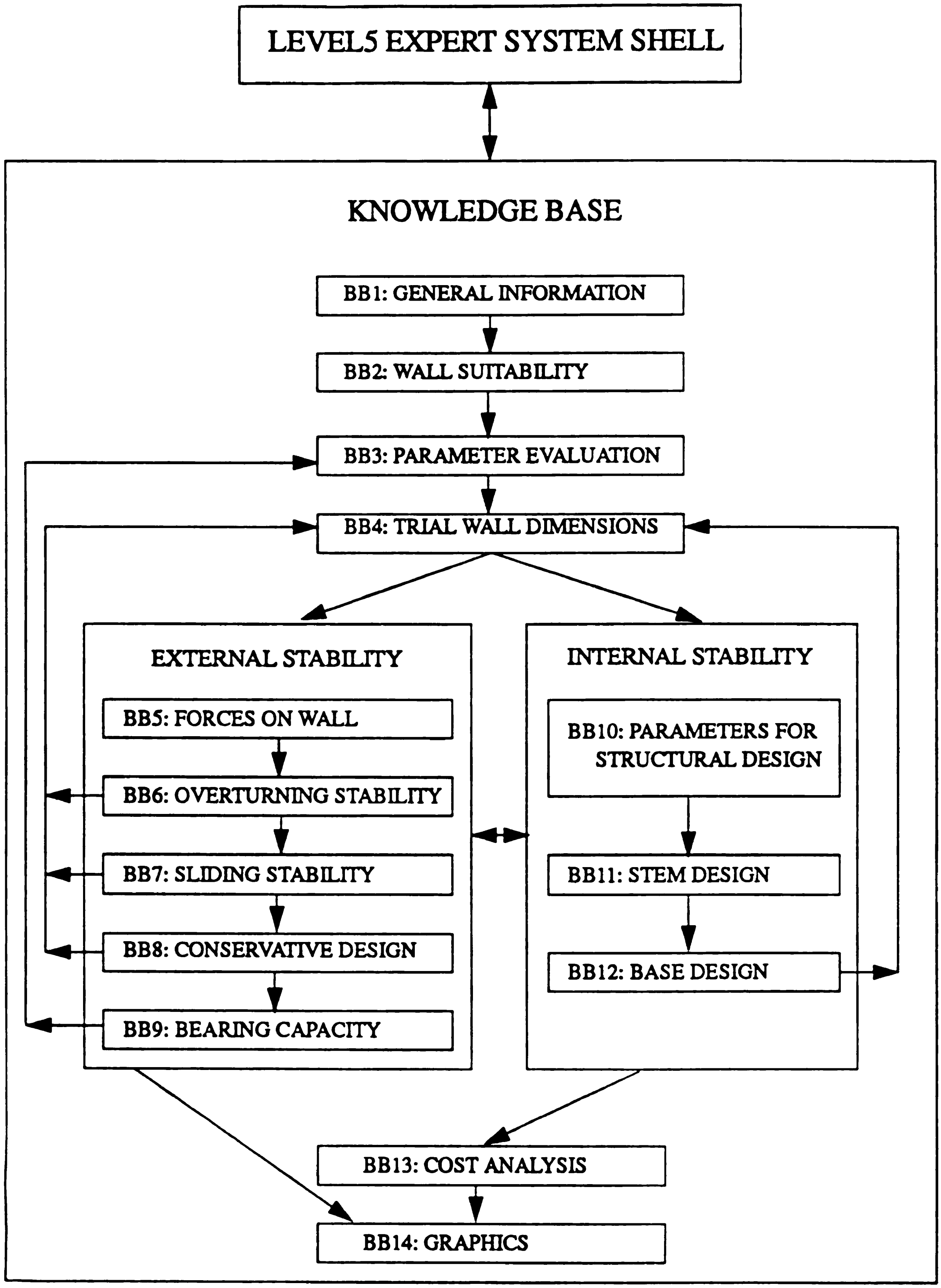


Figure 4.1 Structure of building blocks in TWALL

4.2 Building Blocks of TWALL

The BB's of TWALL are described briefly in the following sections.

4.2.1 BB1: General Information

BB1 contains rules that interactively acquaint the user with the purpose, capabilities and limitations of the expert system TWALL. It also gathers the basic information whether the user wishes to design the wall for external stability only or both external and internal stability. The heuristics that guided the design of this BB dealt mostly with developing a comfortable interface for the user.

4.2.2 BB2: Wall Suitability

BB2 contains rules to check the suitability of a cantilever retaining wall for a given application. The user has an option to over-ride the recommendations made by the system and continue with the design. The main purpose of this BB to show the capabilities of expert systems for solving the deductive type of problems. The inference network of this BB is shown in Figure 4.2.

4.2.3 BB3: Parameters Evaluation

The inference network of BB3 is shown in Figure 4.3. This BB contains rules that query the user for the required

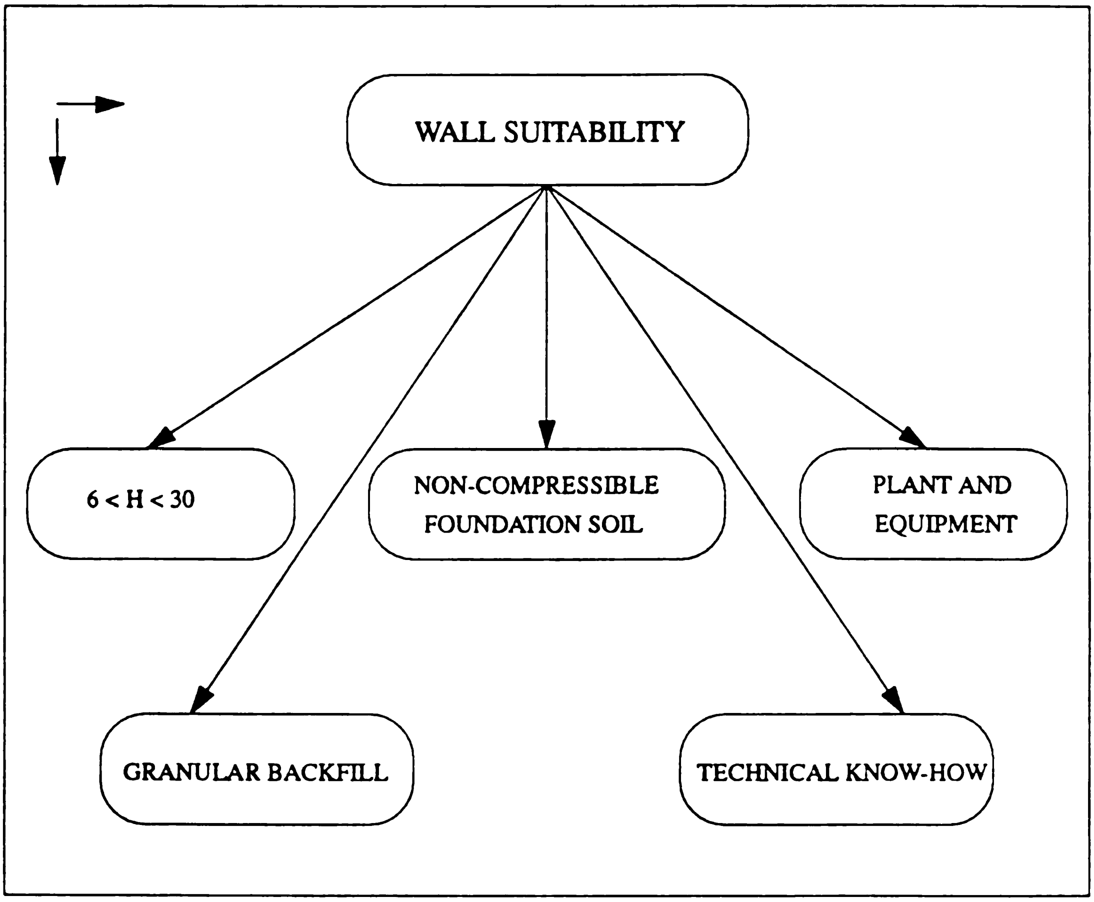


Figure 4.2 Inference network for wall suitability

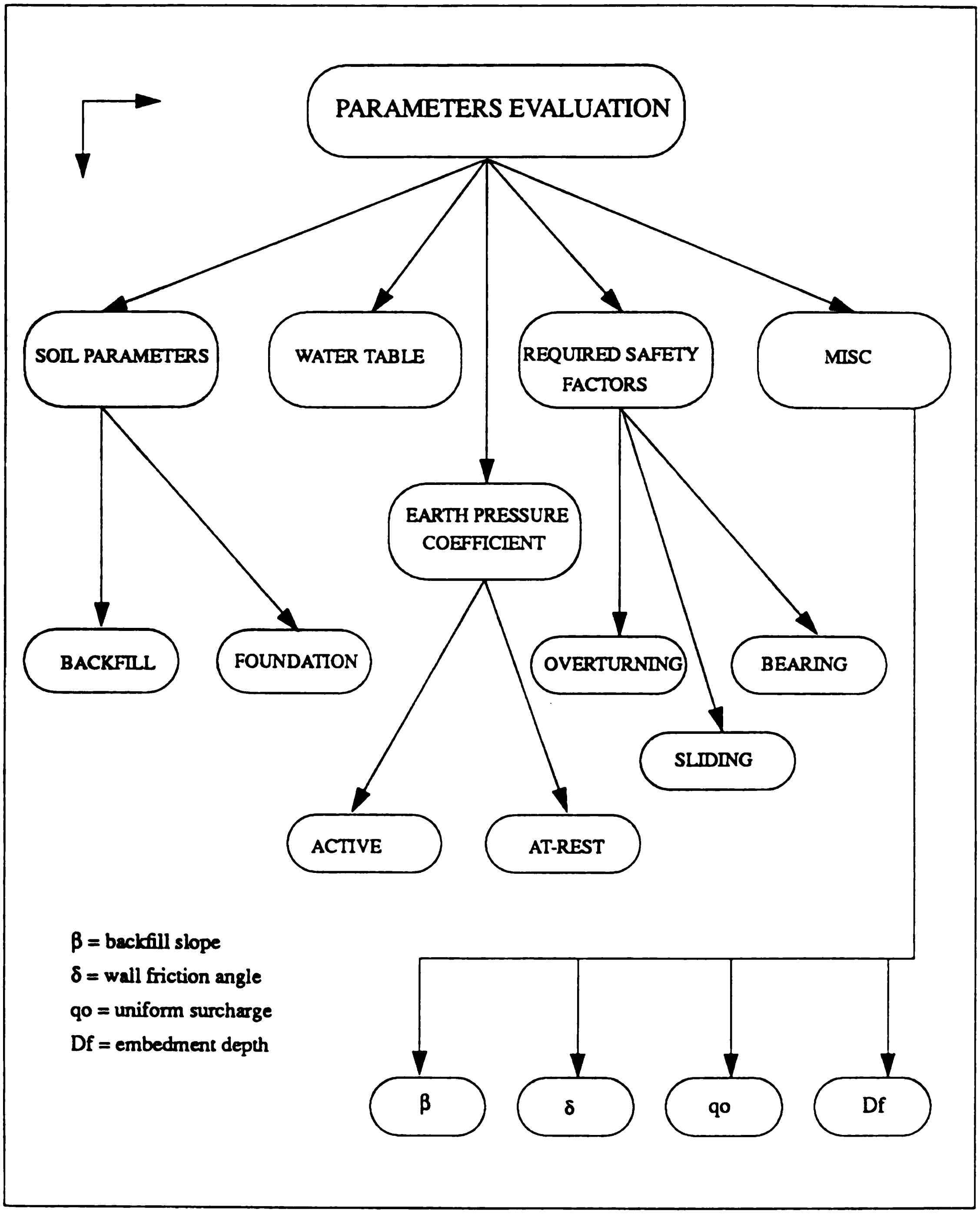


Figure 4.3 Inference network for parameters evaluation

design parameters. These parameters include soil friction angle and unit weight, backfill slope angle, wall friction angle, surcharge, water table and required safety factors for wall stability against overturning, sliding and bearing capacity failures. Making use of heuristics incorporated in the knowledge base, the system displays permissible limits and recommended values of the parameters for guiding the user when queried. See Chapter 7 for heuristics development.

The system provides default values for some of the parameters including wall friction angle and required safety factors. The default values used by the system are displayed with the query and the user has an option to either use the default values or make changes according to the guidelines provided in the query. See example run (Appendix B) for sample queries. As an example, a sample query for wall friction angle and user response is illustrated below:

```
Do you want to enter wall friction angle of your choice?
Enter "TRUE"
If "FALSE" the system will assume default wall friction
angle i.e., δ=(β+Φ)/2=26.7
Press <F5> function key to know more about wall
friction.
                                   TRUE      FALSE

     Wall friction angle (δ) ?
     Permissible values: 10.0 <δ< 35.0  deg

                                   18.43
```

The system calculates default wall friction angle δ based on heuristic (i.e., $\delta=(\beta+\phi)/2$) developed in this study. The rules of this building block also query the user regarding the assumption to be made for computing earth pressure coefficient (active or at-rest). For the active choice, the system assumes Coulomb's active conditions and computes the earth pressure coefficient K using equation 2.2. The user can also use Rankine's equation assuming $\delta=\beta$ because Coulomb's and Rankine's equations yields the same results for $\delta=\beta$. For the at-rest choice, the system computes earth pressure coefficient using Jaky's equation or modified Jaky's equation for sloping backfill (equation 2.9 and 2.10).

4.2.3.1 Data Screening

The input data enters TWALL through queries to the user. It is important to scan the incoming data so that user mistakes in responses to the query can be detected and rectified there and then. Heuristic rules are used to specify the reasonable and practical limits for the input parameters.

If any error is detected by the system in the input data, a message "out of range" is displayed to the user and the system queries the user again with the same question. This format allows immediate correction of any mistake in the incoming data.

In the following sample rule if the user makes some mistake in entering the data, the DISPLAY statement displays the message "out of range" to the user, the FORGET statement removes all facts pertaining to base length B from the session context, the CYCLE statement moves control again to the top of the rule and the user is again queried with the same question.

```
RULE backfill internal friction angle
IF   Φ1>=20
AND  Φ1<=45
THEN know Φ1
ELSE DISPLAY out of range
AND  FORGET Φ1
AND  CYCLE
```

4.2.4 BB4: Trial Wall Dimensions

The rules in BB4 queries the user for base, heel and top stem thickness. The heuristics incorporated in these rules not only recommend an appropriate range for the desired parameter but also guide the user to a reasonable response by limiting the maximum and minimum ranges of the parameter being queried. A sample rule below demonstrates this ability.

```
RULE  base width
IF    HwD>0
AND   Ba:=0.4*H
AND   Bb:=H
AND   Ba1:=0.6*H
AND   Bb1:=0.7*H
AND   B >=0.4*H
AND   B <=H
THEN  know B
```

The above rule queries the user about base length which is a function of wall height H. This rule applies when water level on heel side of the wall is above the base. "Ba" and "Bb" are maximum allowable base lengths (maximum expected range) and "Ba1" and "Bb1" are recommended base lengths (based on experience of TWALL development). These recommended and maximum base lengths are displayed when user is queried about the base length. In this way, the user is guided to respond to a query by making use of experience of the experts on the design of retaining walls. The last two facts before THEN part of the rule impose minimum and maximum limits for B on the user for his or her response. See example run for sample query (Appendix B).

Shear reinforcement (i.e., stirrups) is not commonly used in the design of cantilever retaining walls. Therefore, the stem thickness should be sufficient to resist critical shear without any steel reinforcement. The system computes bottom stem thickness where shear is maximum by equating total horizontal force on stem (equation 2.22) to the shear strength of concrete (equation 2.32). Finally, the system computes initial toe length by subtracting heel and stem bottom thickness from the base length.

The heel is designed as cantilever beam where steel reinforcement is provided at the top of the heel to carry tensile stresses. A short toe may result in a situation where upward soil pressure exceeds the downward soil pressure at the intersection of heel and stem which is not desirable from structural design point of view (see Chapter 5 for a detailed discussion). Using heuristics derived from parametric sensitivity analysis, the rules in the building block limit toe length to not less than 24 to 30 percent of base length depending on wall angle friction and wall height. Thus, a situation as mentioned above is avoided. As an example, the following rule recomputes toe and base lengths when computed toe length is less than minimum required toe length.

```
RULE toe length
IF   toe<toemin
THEN know toe
AND  toe:=toeMin
AND  B:=toe+tsb+heel
```

4.2.5 BB5: Forces on Wall

The rules in BB5 perform the extensive computational task of calculating effective horizontal and vertical forces on the wall (Figure 2.7). The effects of wall friction angle, backfill slope angle, water table and uniform surcharges on the wall have been incorporated in these rules.

For computing lateral earth forces on the wall, the system assumes a linear earth pressure distribution behind the wall. The uplift force under the base due to water is computed by assuming that water pressure varies linearly along the base. The upward soil pressure under the base is also assumed to vary linearly under the base. Earth forces on toe side of the wall and soil weight over the toe are neglected in these computations. See Chapter 2 for details.

4.2.6 BB6: Overturning Stability

The rules in BB6 are structured to compute overturning moments, resisting moments and the safety factor against wall overturning. The rules use equations 2.14 through 2.16 for these computations. The inference network of BB6 is shown in Figure 4.4. The rules in BB6 are designed such that when the trial wall design fails in overturning, the system increases both the base and heel length. However, the increase in base length is five percent more than the heel length in each iteration during the trial design process. The net result is a lengthened toe which improves wall stability against overturning more effectively than the increase in heel length.

The heuristics incorporated in BB6 were deduced from parametric sensitivity analysis and were further refined and quantified through simulation and experimentation. As an example, it is generally known that increasing heel and toe lengths improve overturning stability and from parametric sensitivity analysis it was found that increasing toe improves wall stability against overturning more effectively than the heel length. But it is not known that how much these dimensions should be increased when trial design fails in overturning.

Neither exact mathematical models are available nor they can be easily developed to quantify these dimensions because of large number of variable involved and their interrelationship. Thus, the empirical expressions given below to quantify the required increase in the base and heel lengths when trial design fails in overturning were developed through simulation and experimentation. In other words, these expressions were developed by running the program with

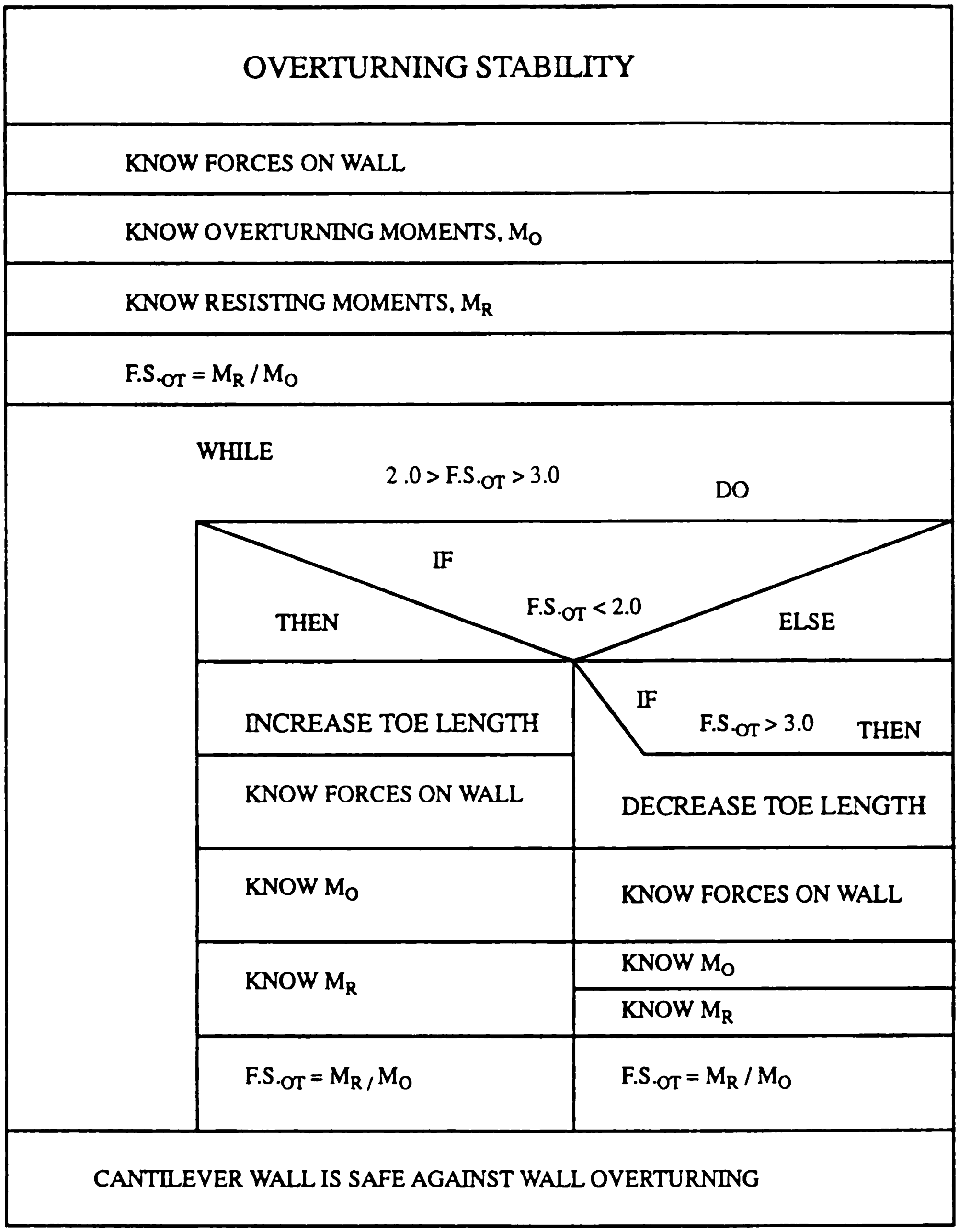


Figure 4.4 Inference network for wall stability against overturning

different values of design parameters (within the practical range) and studying their effects on wall stability against overturning.

$$B = (CF)B+B(I)(F.S.otReq-F.S.otAval)/F.S.otAval \;\dots\;\dots\dots\dots \quad (4.1)$$

$$heel = (CF)heel+heel(1)(F.S.otReq-F.S.otAval)/F.S.otAval) \;\dots\dots\dots \quad (4.2)$$

where CF is a convergence factor, I is an index value which is 1.00 for this equation, F.S.otReq is required safety factor and F.S.otAval is available safety factor. The CF used with B and heel are 1.15 and 1.10 respectively.

The first term in the above equations provide a constant percent increase in B and heel and the second term provides an increase related to degree which the design lacks the required safety factor. The second term governs equations 4.1 and 4.2 when the difference between the required and the available safety factors is large. But when the difference in required and available safety factors becomes very small the calculated base and heel lengths by the second term also become very small and the system keeps doing unnecessary iterations. To avoid such a situation, a convergence factor was introduced in equation 4.1 and 4.2. The convergence factors reduces the number of iterations by increasing the base length 15 percent and the heel length 10 percent during each iteration. A higher CF is used with B so that net effect of increasing in the base and heel lengths is a lengthened toe. The following rule shows the use of equations 4.1 and 4.2.

```
RULE  safety against overturning
IF    F.S.otAval<F.S.otReq
AND   Br:=100*(F.S.otReq-F.S.otAval)/F.S.otAval+15
AND   heelr:=100*(F.S.otReq-F.S.otAval)/F.S.otAval+10
AND   DISPLAY overturning failure
AND   FORGET cantilever wall design is safe
.
.
AND   B:=1.15*B+B*(F.S.otReq-F.S.otAval)/F.S.otAval
AND   heel:=1.10*heel+heel*(F.S.otReq-F.S.otAval)
            /F.S.otAval
AND   CYCLE
AND   F.S.otAval:=Mr/Mo
AND   F.S.otAval>=F.S.otReq
THEN  wall is safe against overturning moments
```

This rule is activated when the trial wall design fails in overturning. To achieve the goal, (i.e., wall is safe against overturning moments) the inference mechanism of TWALL tries to establish all facts in the rule starting from the top. "Br" and "heelr" are recommended percent increase in base and heel length that are displayed to the user when the trial design fails in overturning.

The FORGET statements removes all undesirable facts from the session context because these need to be re-established for after base and heel length are modified. If these facts are not removed from the session context, the inference mechanism will not pursue the goals that need to be re-established with modified wall dimensions. The facts with "B" and "heel" compute the required increase in the base and heel lengths. The user has an option to either accept the default percent increase in base and heel length or change these values by using CHNG function of LEVEL5. The CYCLE statement makes the system recompute all removed facts from session context with increased base and heel lengths.

Finally, the available safety factor is recomputed and compared with the required. This iterative process continues until the available safety factor exceeds the required safety factor. See Appendix B for a sample interaction of the system with the user.

4.2.7 BB7: Sliding Stability

The inference network of stability of the wall against sliding failures is shown in Figure 4.5. The rules in BB7 are structured first to query the user whether to design the wall with or without a base key and then to compute the safety factor against wall sliding.

For walls designed with base key, the system considers passive resistance only in front of the key. The system limits key depth between 1 feet to 0.5B. To simplify calculation of shear resistance under the base with the key, TWALL assumes rupture surface passing through the bottom of the key and parallel to the wall base. The passive resistance in front of the wall above the bottom of the base is neglected for all cases.

Heuristic rules derived from parametric sensitivity analysis and knowledge obtained from the experts on retaining wall design were used to improve the design algorithms for wall stability against sliding. It is known from parametric sensitivity analysis that increasing base and heel length improve wall stability against sliding but an increase in heel length improves wall stability more

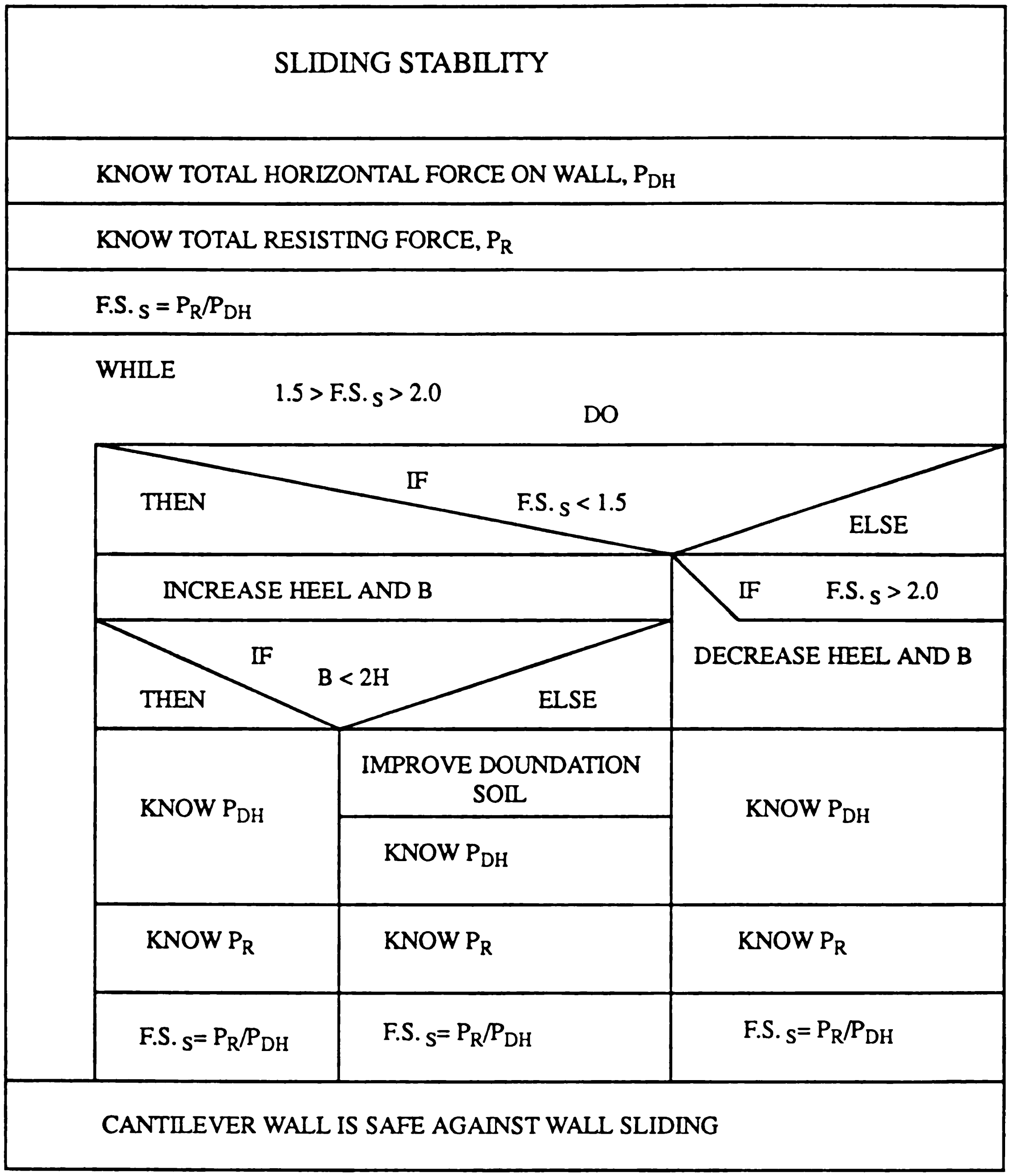


Figure 4.5 Inference network for wall sliding stability

effectively than an increase in base length.

The developed expressions to increase base and heel length are given below. These expression were developed by running the program with different values of design parameters and studying the effect of change in these parameters on wall stability against sliding failures.

```
B    = (CF)B+B(I)(F.S.sReq-F.S.sAval)/F.S.sAval ................ (4.3)
heel= (CF)heel+heel(I)(F.S.sReq-F.S.sAval)/F.S.sAval ........... (4.4)
```

where F.S.sReq is required safety factor and F.S.sAval is available safety factor against sliding failures. The CF used with B and heel are 1.03 and 1.07 respectively. It is to be noted that higher CF is used with the heel so that net effect of increase in base and heel lengths is a lengthened heel. The index value I for these equation is also unity. These above expressions use the same logic as those previously described for overturning stability in BB6.

In weak foundation soils, the required base length becomes excessively large to meet the sliding stability requirements and wall dimensions fall out of proportions. If such a situation arises in TWALL, the rules in this BB temporary halt the design process and advise the user to consider improving the foundation soil parameters i.e., the unit weight and the soil friction angle. Then the design is repeated with new foundation soil parameters. This interactive process continues until wall dimensions with reasonable proportions are obtained. In this knowledge base, the base length is considered excessively large when it exceeds twice the wall height.

4.2.8 BB8: Conservative Design

According to the knowledge base of TWALL, the design of a cantilever retaining wall is considered as conservative when safety factors against wall sliding and overturning exceed 2 and 3.0 respectively. These limits are upper bound values that could be found in literature on the design of retaining structures (Das 1984, Bowles 1988).

The safety factor against sliding usually controls the wall design as known from the parametric sensitivity analysis. Therefore, the expressions developed in this study to make the design economical are based on sliding stability requirements. The developed expressions as given below reduce the base and the heel lengths according to the difference between the available and required safety factors against sliding failures. The system recalculates all forces and moments on wall with modified B and heel and then recheck overturning and sliding safety factors.

```
B    = (CF)B-B(I)(F.S.sAval-F.S.sReq)/F.S.sAval ................. (4.5)
heel= (CF)heel-heel(I)(F.S.sAval-F.S.sReq)/F.S.sAval ............(4.6)
```

where CF is a convergence factor and I is an index value. The convergence factor for both B and heel is 0.95 and index values are 0.35 and 0.4 for B and heel respectively. Small index values are used in the above expressions to reduce the effect of second term when the difference between the required and available safety factor is large. These expressions were also developed in a similar fashion as discussed earlier.

The heuristic developed from parametric sensitivity analysis is that the decrease in heel length substantially reduces the safety factor against wall sliding. The higher index factor used in equation 4.6 with heel reduces heel length five percent more than the base length in each iteration during the trial design process. Thus, the net effect is decreased heel that reduces safety factor against wall sliding to required value in a fewer iterations.

4.2.9 BB9: Bearing Capacity

The inference network of bearing capacity is shown in Figure 4.6. The rules in BB9 compute bearing capacity of the foundation soil and safety factor against bearing capacity failures using equations 2.19 and 2.20 respectively. Making use of heuristics, the rules of this BB also ensure that point of application of resultant of forces acts between the middle third of the base (i.e., eccentricity <B/6) Thus, it is ensured that the whole base remains in contact with the foundation soil.

For example, the specimen rule given below brings the resultant of forces back into middle third of wall base, when it acts out of middle third toward the toe side of the

BEARING CAPACITY

KNOW TOTAL EFFECTIVE VERTICAL FORCE, N

KNOW ECCENTRICITY WITHIN LIMITS, e

KNOW TOTAL ULTIMATE BEARING CAPACITY, Q_{ult}

$F.S._b = Q_{ult} / N$

WHILE $F.S._b < 3.0$ DO

IMPROVE FOUNDATION SOIL OR INCREASE EMBEDMENT DEPTH

KNOW N

KNOW e

KNOW Q_{ult}

$F.S._b = Q_{ult} / N$

CANTILEVER WALL IS SAFE AGAINST BEARING CAPACITY FAILURES

Figure 4.6 Inference network for wall stability against bearing capacity failures wall (Figure. 2.8). This rule interactively increases the heel and base length and recomputes the location of the resultant. The interactive process continues until the resultant acts within the middle third of the base.

```
RULE eccentricity
IF   e>=0
AND  e>B/6
AND  DISPLAY eccentricity out of limits
.
AND  heel:=1.05*heel
AND  B:=1.02*B
AND  CYCLE
AND  x:=(Mr-Mo)/N
AND  e:=0.5*B-x
AND  e<=B/6
THEN know eccentricity within limits
```

The rules in BB9 also advise the user to improve foundation soil or increase embedment depth when its fails in bearing. The specimen rule is:

```
RULE safety factor against bearing
IF   F.S.bAval<F.S.bReq
AND  DISPLAY bearing capacity failure
AND  FORGET Φ2
.
AND CYCLE
AND F.S.bAval:=Qult/N
AND F.S.bAval>=F.S.bReq
THEN wall is safe against bearing capacity failures
```

The above rule is activated when the available safety factor falls below that required. The DISPLAY statement in the rule displays the message to the user regarding wall the failure due to weak foundation soil and renders advice to improve foundation soil. The FORGET statement removes the facts that need to be modified in the session context and the CYCLE statement makes the program re-establish the forgotten facts either through computations or through queries from the user. In this case, the system queries the user for embedment depth Df, foundation soil friction angle $\phi 2$ and cohesion c2 and recomputes the safety factor against bearing capacity failures. However, the user also has an option to modify wall dimensions (e.g., base and heel) through "WHY" function of LEVEL5. This interactive process continues until the available safety factor exceeds the required.

4.2.10 BB10: Parameters for Structural Design

The rules in BB10 are structured to query the user for the design parameters required for the structural design of stem and the base. These parameters include the compressive strength of concrete f'_c, yield strength of steel f_y and overload factors. The allowable ranges of f_y and f'_c are displayed to the user when queried. Default values of overload factors for stem, heel and toe design are provided but the user has an option to change the default values. The user also has an option to either consider or neglect upward soil pressure under the base for the heel design.

4.2.11 BB11: Stem Design

The rules in this BB are structured to compute pressures, shears and moments at five different locations along stem height (i.e., stem top, 1/4, 1/2 and 3/4 of stem height and stem bottom). Pressures, shears and moments are computed using equation 2.21, 2.22 and 2.23 respectively. The forces considered for the structural design of stem are shown in Figure 2.9.

The strength design method of ACI Code (ACI 318-89) is followed for computing required steel reinforcement at top, middle and bottom of the stem. The computed steel is then checked for minimum and maximum allowable limits as specified in the Code. The system uses the default top stem thickness (i.e., 12 inches) or any value as preferred by the user. The bottom stem thickness is computed by equating the compressive strength of concrete to the shear at stem bottom as discussed earlier. See Figure 4.7 for the inference network of stem design.

4.2.12 BB12: Base Design

The inference network of this BB is shown in Figure 4.8. The rules in BB12 compute pressures, shears and moments on the heel and toe using equations 2.24 through 2.29 and Figure 2.9. These pressures, shears and moments are computed at five different locations along the heel and toe (i.e., free ends, 1/4, 1/2 and 3/4 of heel or toe and points where heel and toe join stem). The user has an option to either include or neglect upward soil pressure under the heel to compute shear and moments on heel.

Shear usually controls the design of the heel and toe.

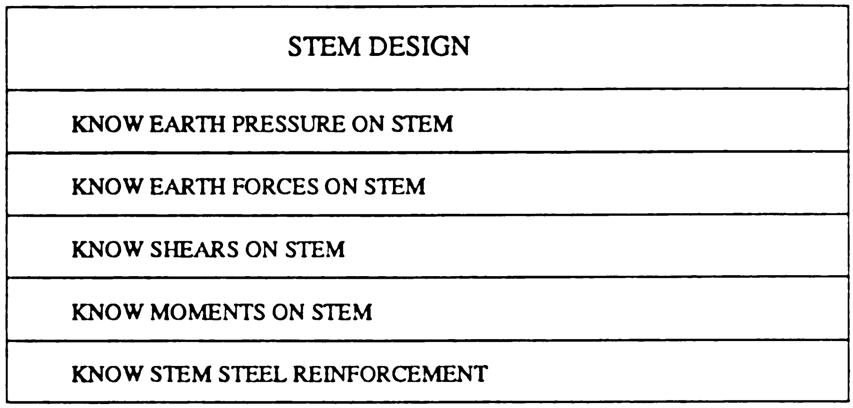


Figure 4.7 Inference network for stem design

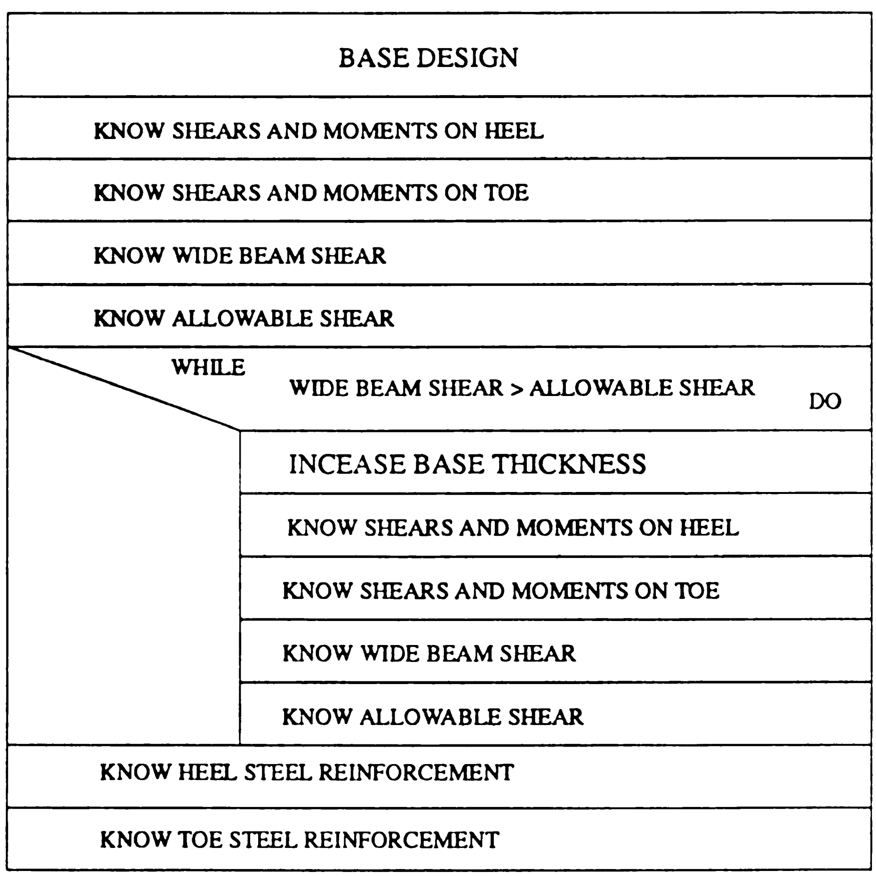


Figure 4.8 Inference network for base design

Therefore, the rule in this BB are design to first check the heel and toe for wide beam shear before computing required steel reinforcements. The larger of shears computed on heel and toe is taken as the critical shear and the base is checked for this shear so that the critical shear does not exceed the compressive strength of base concrete.

When wide beam shear exceeds the compressive strength of concrete, the system recommends an increase in base thickness to the user and waits for his or her response. Then the system recomputes shear strength of the base with increased base thickness and compares it again with the critical shear. This interactive process continues until the shear strength of the base concrete exceeds the wide beam shear. The expression developed for increasing the base thickness in each iteration is given below:

$$tb=1.1tb+0.45tb(Vwidebeam-\Phi Vc)/\Phi Vc \quad \text{.................. (4.7)}$$

where tb is a base thickness, Vwidebeam is a critical shear on the base and ΦVc is a allowable compressive strength of concrete. The convergence factor of 1.1 and index factor of 0.45 were developed through a trial and correction process.

The rest of the rules in this BB compute required steel reinforcement for heel and toe and check for their allowable minimum and maximum limits. The steel requirement is computed at three different locations along heel and toe namely, at free ends, middle and at the points where heel and toe joins stem. Heel and toe are also designed according to the ultimate strength method of the ACI Code.

4.2.13 BB13: Cost Analysis

The rules in BB13 compute required quantities of excavation, backfill and concrete and cost per lineal feet of the wall. The default cost of materials is based on Means Construction Cost Data 1991. The user has an option to change the default cost of materials during design process. The inference network of BB13 is shown in Figure. 4.9.

4.2.14 BB14: Graphic Interface

The structure of the external graphics program GTWALL coded in Microsoft FORTRAN is shown in Figure 4.10.
A procedural rule in BB14 interacts with GTWALL. The control commands in this BB activate and send final design dimensions of the wall to GTWALL through a disk file. GTWALL receives incoming data from TWALL in a specific format, checks for current video configuration, draws the wall design sketch with all its dimensions and waits for user response. On the user response, the program control is shifted back to LEVEL5 and the inference mechanism terminates the current session and activates various function keys that can be used by the user to perform various task (e.g., save the current session context, check the reasoning process of wall design, restart the program or exit the program).

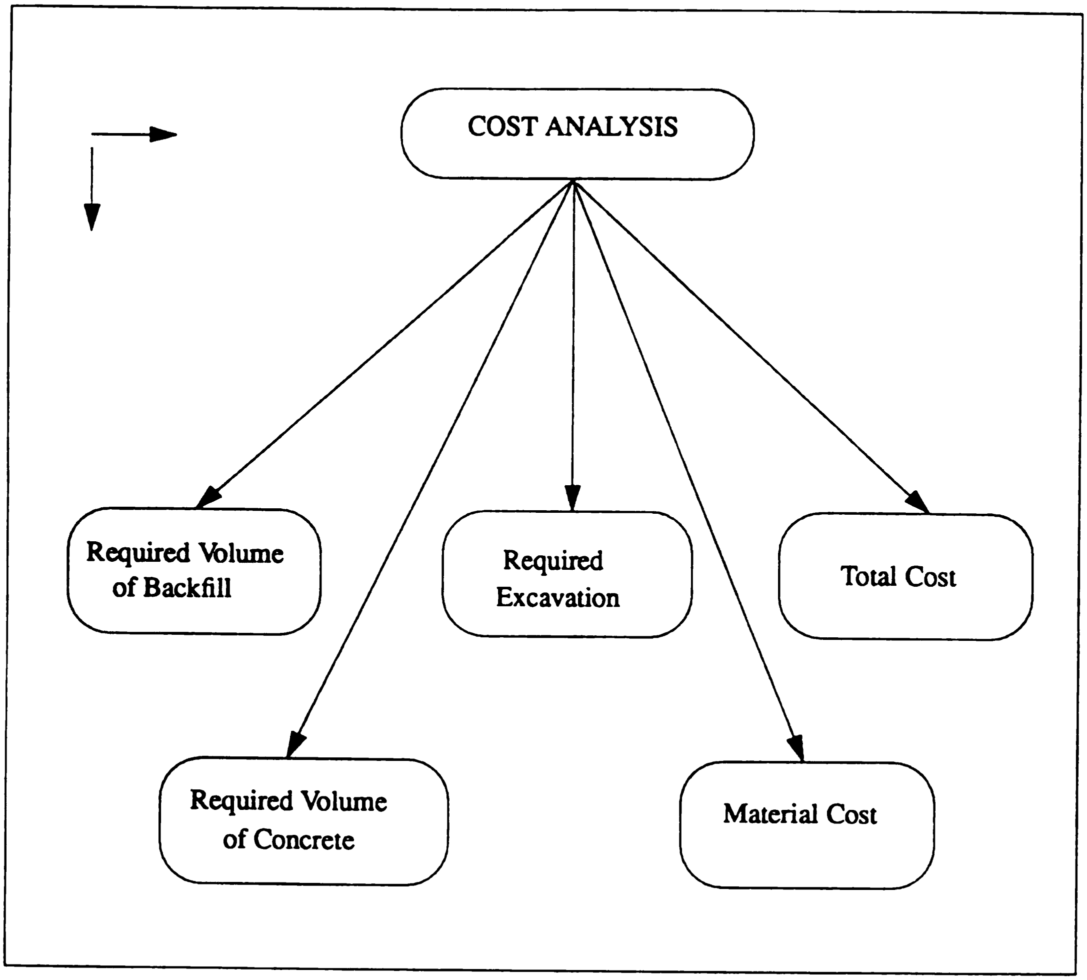


Figure 4.9 Inference network for cost analysis

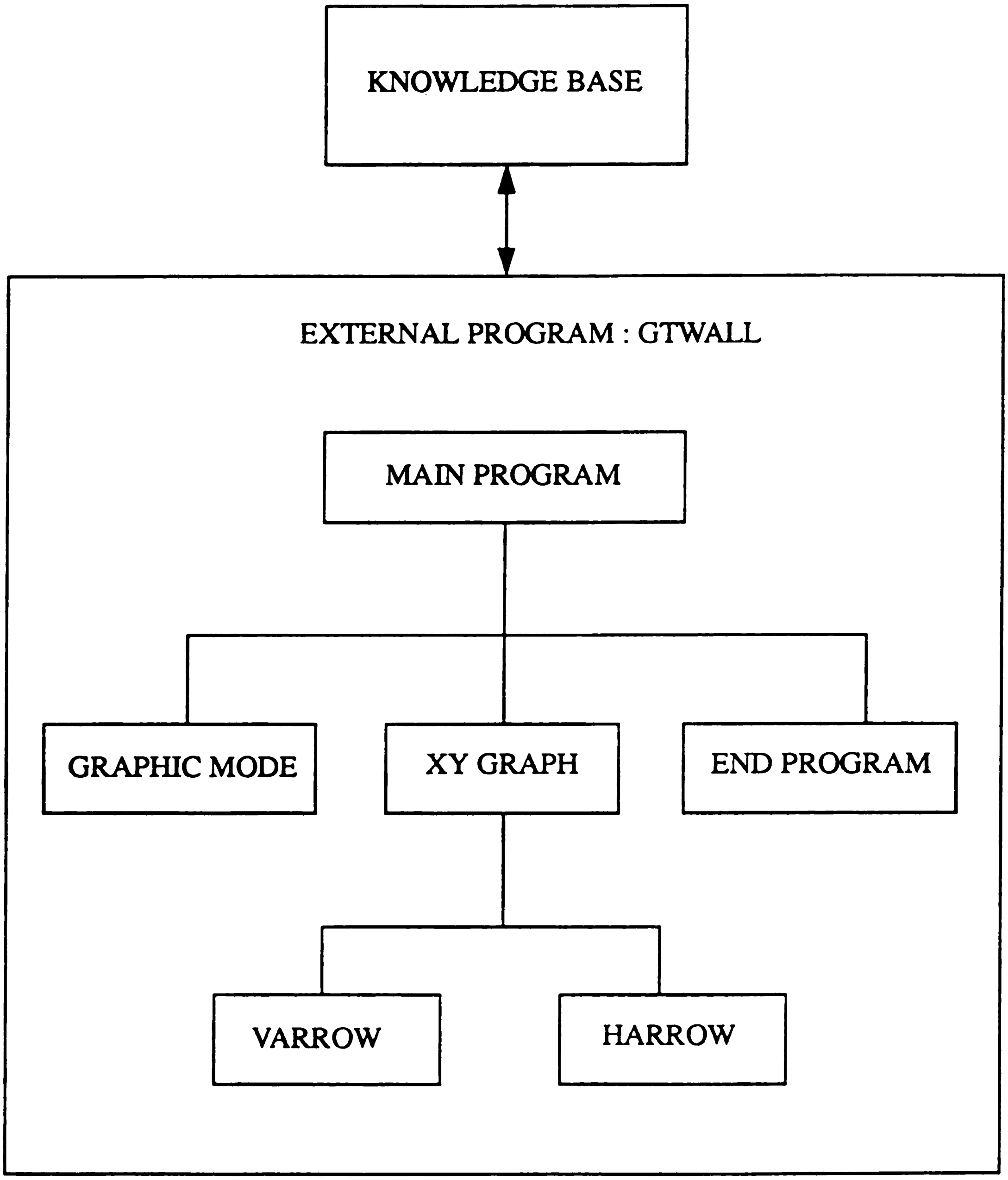


Figure 4.10 Structure of external program GTWALL

4.3 Examples of the Design Process

In the process of development and expansion of TWALL, over a hundred cantilever wall designs were made using TWALL (e.g., 34 walls were designed for a class on retaining structures (CE 419), see appendix D). From these designs, it was found that, TWALL typically makes 3 to 4 iterations to obtain the design. The number of iterations in TWALL have been minimized by incorporating the heuristics as discussed in the previous sections. The reduction in iterations have reduced the computational time to less than a minute on XT computers.

A complete design process of TWALL and its interaction with the user is shown in appendix B. In general, the design process of the cantilever wall on TWALL is summarized in Figures 4.11. The Figure shows changes in base length, heel length and overturning and sliding safety factors after each iteration when lower limits of trial dimensions recommended by TWALL were used. As can be seen from the figure that TWALL reaches the optimal design in 3 iterations. A few sample TWALL interactions with the user are shown below. The user responses are hatched for clarity.

```
Base width  (B) ?

 Recommended width:   12.50 <B< 15.00  ft
 Permissible width:   10.00 <B< 25.00  ft

                      12.50
```

Heel length ?

Recommended length: 7.12 <heel< 7.50 ft
Permissible length: 6.25 <heel< 8.12 ft

6.90

O V E R T U R N I N G   F A I L U R E

The wall design is unsafe as the safety factor against overturning moments **1.54** is less than **2.00**. The system will increase **39.6 %** heel length and **44.6 %** base length, as you press <Enter> and it will recalculate the safety factor against overturning. However, you have an option to increase base and heel lengths of your choice using "WHY" and "FACTS MENU".

B	= 12.68	ft
Heel	= 6.90	ft
Toe	= 3.25	ft

Please press <Enter> to continue

S L I D I N G   F A I L R E

The wall design is unsafe against sliding forces as the safety factor **1.44** is less than **1.5**. The system will increase **11.1 %** heel and **7.1 %** base length as you press <Enter> and it will recalculate safety factor. However, you have an option to increase heel and base lengths of your choice using "WHY" and "FACTS MENU".

F.S.overturning	= 2.81	
B	= 18.34	ft
Heel	= 9.63	ft
Toe	= 3.25	ft

Please press <Enter> to continue

I N S U F F I C I E N T   B A S E   T H I C K N E S S

The wall design is unsafe due to insufficient base thickness for wide beam shear. The system will increase **17.78 %** base thickness as you press <Enter> and will again check the base for vide beam shear.

tb	= 1.80	ft
ΦVc	= 20224	Ibs
Vwidebeam	= 23771	Ibs

Please press <Enter> to continue

D E S I G N   S U M M A R Y

Safety factor against wall overturning		= 3.21
Safety factor against sliding failures		= 1.54
Safety factor against bearing failures		= 4.55

Wall height	ft	= 25.0
Wall height above ground surface	ft	= 22.00
Stem height	ft	= 22.88
Top stem thickness	ft	= 1.00
Bottom stem thickness	ft	= 2.53
Base width	ft	= 19.64
Heel length	ft	= 10.70
Toe length	ft	= 6.41
Base thickness	ft	= 2.12
Stem steel	sq-in/ft	= 1.83
Heel steel	sq-in/ft	= 1.98
Toe steel	sq-in/ft	= 0.88
Cost	$/ft	= 937.38

The design process of TWALL with a bad guess of soil parameters and trial wall dimensions are shown in Figure 4.12. The figure shows changes in base length, heel length and overturning and sliding safety factors with the number of iterations. As can be seen from this figure that even with the bad guess of input parameters, TWALL reaches the safe design in 6 iterations. This number is small as compared to the numerous iterations made by procedural programs developed for problems having open-form solution such as the design of cantilever retaining wall.

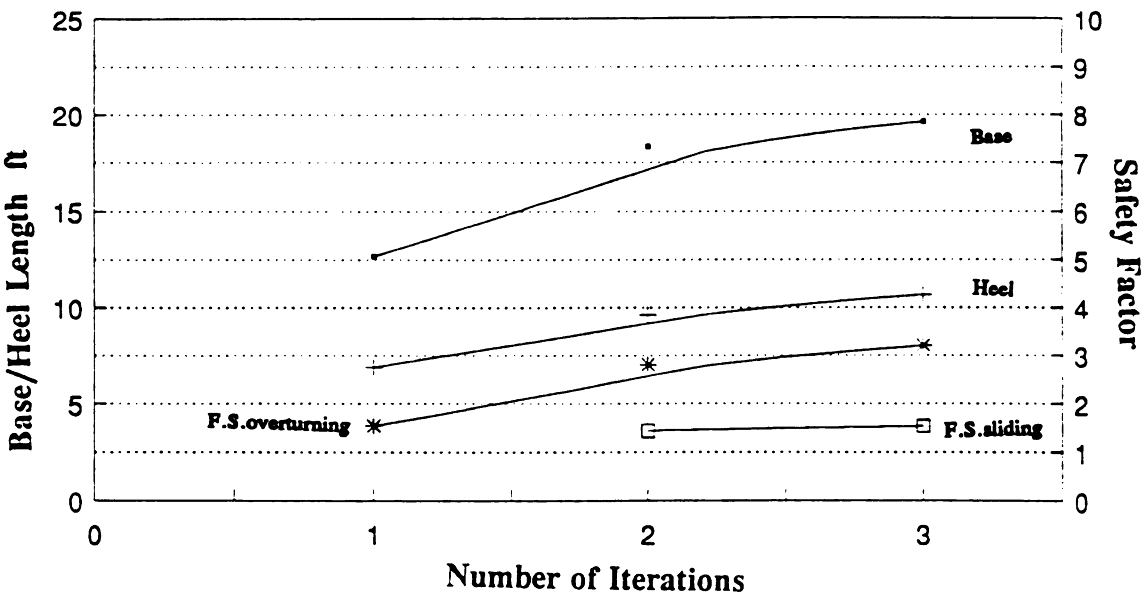


Figure 4.11 TWALL design process when trial wall dimensions recommended by TWALL are used

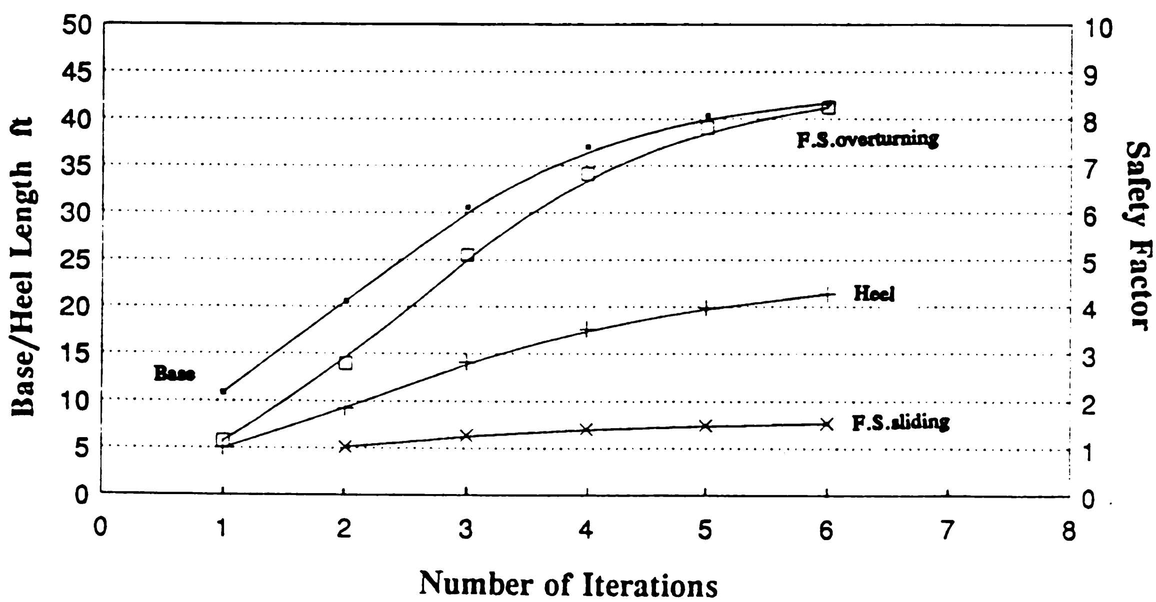


Figure 4.12 TWALL design process with bad guess of soil parameters and trial wall dimensions

CHAPTER 5

PARAMETRIC SENSITIVITY ANALYSIS

5.1 General

The proportions of a well-designed cantilever retaining wall are influenced by a number of variables. These include wall height, backfill strength and density, foundation soil strength, wall friction, backfill slope and water table. This chapter summarizes the results of a series of parametric sensitivity analyses performed to study the interrelationships among these variables, wall proportions and safety factors. The results of these analyses were used for writing heuristics (rules of thumb). These heuristics were then incorporated in the expert system TWALL during its expansion.

The analyses were carried out in two parts. In the first part, a sensitivity analyses were performed to evaluate the effect of change in these variables on safety factor against wall overturning, sliding failures and bearing failures. The analysis was performed by varying each variable within a typical range and computing the safety factor while keeping the other variables constant. This method reveals not only the sensitivity but also the direction of the change in safety factor to a change in any variable.

In the second part, a specific study was made of the effect of change in heel length on the distribution of net downward pressure on the heel. The analysis was first performed assuming horizontal backfill, neglecting wall friction and considering the water table at wall base. Then, the effects of backfill slope, wall friction and water table on the distribution of pressure on the heel were studied.

5.2 Assumptions

The following assumptions were made for the present parametric sensitivity analyses:

a. The backfill soil is cohesionless and characterized by an internal friction angle, $\phi 1$ and unit weight, $\gamma 1$.
b. The foundation soil is either cohesionless or cohesive and characterized by an internal friction angle, $\phi 2$, cohesion, c2 and unit weight, $\gamma 2$.
c. Coulomb's active conditions were assumed behind the wall and passive resistance in front of wall was neglected.

5.3 Effect of Changes in Variables on Wall Stability

5.3.1 Method of Analysis

The expert system TWALL (Chapter 3 and 4) was used for the parametric sensitivity analysis. The analysis was performed as follows:

a. A realistic range for each variable (X) was selected that brackets most commonly-encountered design situations. The midpoint value (Xmid) and the maximum difference (ΔXmax) between the midpoint value and extreme values was computed for each variable (Table 5.1).

b. The change index (ΔX) for each variable (X) was computed as the ratio of deviation of X from Xmid to ΔXmax

$$\Delta X(\%) = \frac{X - Xmid}{\Delta Xmax} 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.1)$$

where $\Delta Xmax = Xmax - Xmid$

c. A "midpoint" base safety factor (Fo) was computed using the median value of all variables and wall proportions (Table 5.2).

d. A safety factor (Fx) was computed as each variable was varied across the range.

e. The relative change in safety factor (ΔF) as a percent of Fo was calculated as:

$$\Delta F(\%) = \frac{Fx - Fo}{Fo} 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

Table 5.1 Range of variables

Parameter (X)		Unit	Xmin	Xmid	Xmax	ΔXmax
Wall height	H	ft	10	20	30	10
Base Length	B	ft	11	15	19	4
Heel length	heel	ft	6	10	14	4
Backfill unit weight	$\gamma 1$	pcf	90	110	130	20
Backfill friction angle	$\phi 1$	deg	25	35	45	10
Fnd. soil unit weight	$\gamma 2$	pcf	100	120	140	20
Fnd. soil friction angle	$\phi 2$	deg	25	35	45	10
Fnd. soil cohesion	c2	psf	-	0	2000	2000
Wall friction/ϕ1(mid)			0	0.5	1	0.5
Backfill slope/ϕ1(mid)			-0.5	0	0.5	0.5
Water table height/H(mid)			-1	0	1	1

Table 5.2 Base safety factors

Safety factor against overturning, F.S. (ot)	7.77
Safety factor against sliding failures, F.S.(s)	3.63
Safety factor against bearing capacity failure, F.S.(b)	8.78

The base safety factors shown in Table 5.2 appear to be higher than required for an economical design. These safety factors corresponds to active conditions in the backfill. If the wall is designed for at-rest conditions and the other factors like compaction and pore water pressure are also considered, the present design barely meets stability requirements against sliding failures. For example, the base safety factor against sliding failures reduces from 3.63 to 1.48 when considering at-rest conditions with a water table at H/2 from wall base. Also, these base safety factors were kept high so that all parameters could be varied within the specified ranges without reducing actual safety factors below allowable limits.

5.3.2 Results

The effects of change in variables on safety factor against overturning F.S.(ot), sliding F.S.(s) and bearing capacity F.S.(b) failures are shown in Figure 5.1 through Figure 5.4. The effects of changes in the variables on wall design are discussed briefly in the following sections.

5.3.2.1 Wall height

The effects of change in wall height H on three safety factors are shown in Figure 5.4. The factor of safety against wall overturning is more sensitive to change in wall height than to changes in other variables. The reason is that the force causing overturning (leaving aside common variables) is a function of the square of wall height whereas the resisting force is a function of wall height and heel length.

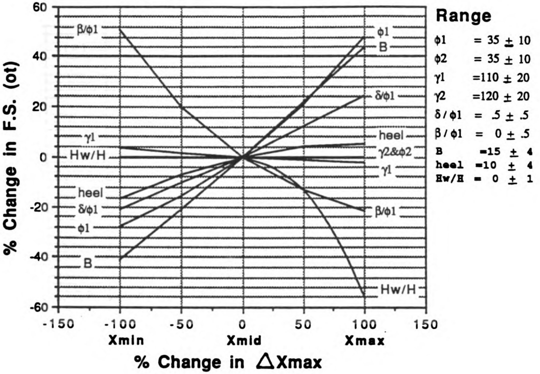


Figure 5.1 Percent change in overturning safety factor versus percent change parameter values

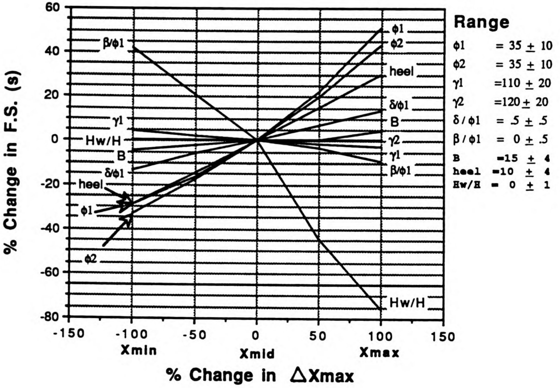


Figure 5.2 Percent change in sliding safety factor versus percent change in parameter values

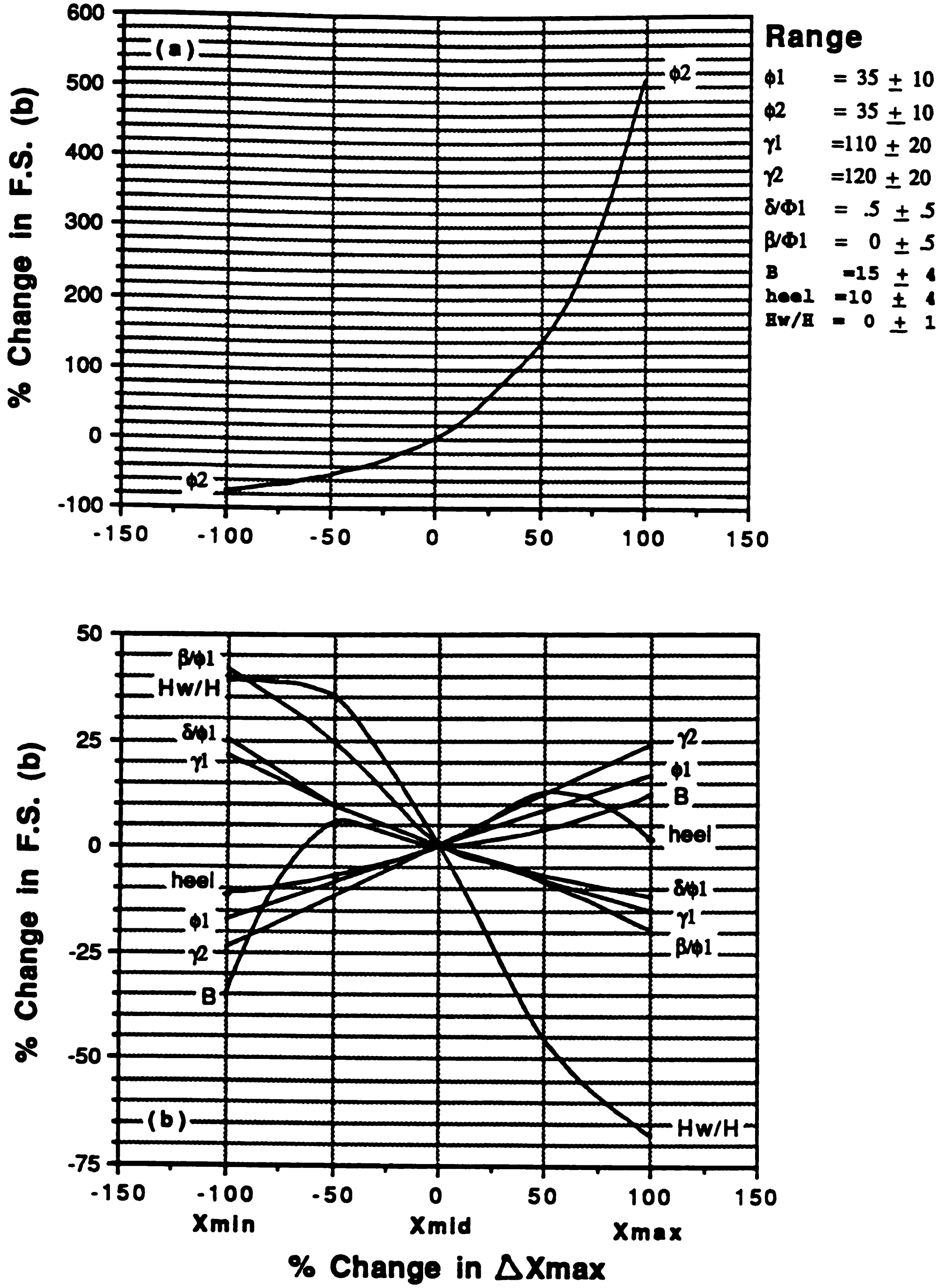


Figure 5.3 (a) and (b) Percent change in bearing safety factor versus percent change in parameter values (Table 5.1)

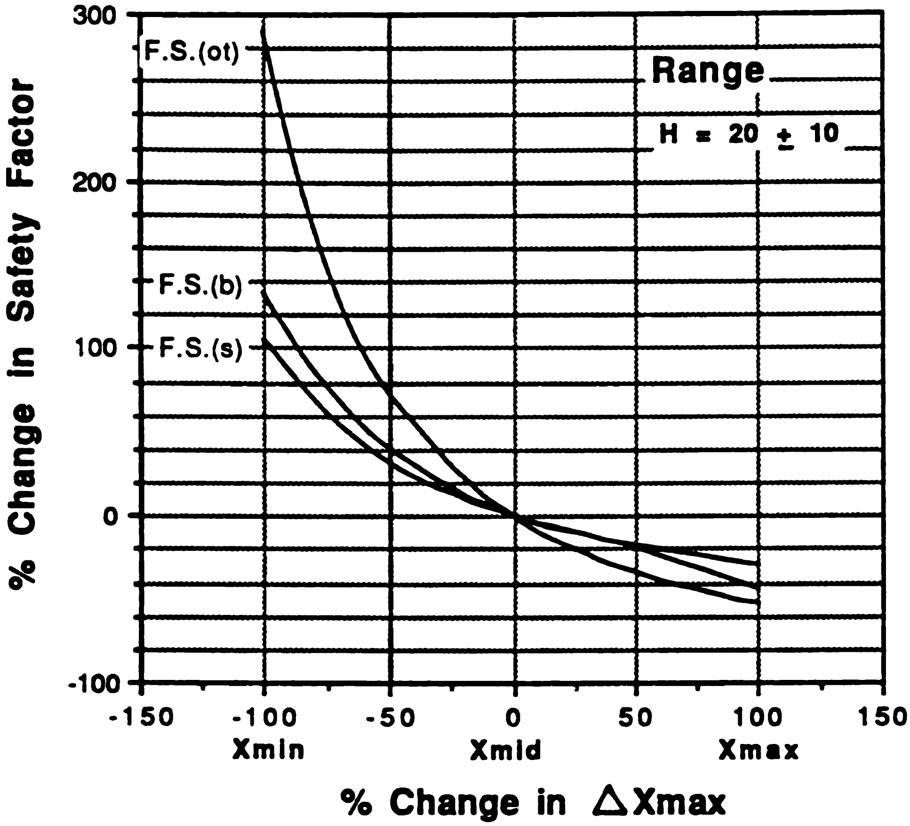


Figure 5.4 Percent change in overturning, sliding and bearing safety factors versus percent change in ΔXmax of wall height (Table 5.1)

As wall height is increased at a fixed value of heel length, the increase in overturning forces and moments is more rapid than the increase in forces resisting overturning. Thus, the overturning safety factor decreases rapidly and the decrease is more pronounced at low values of H. The rise in wall height also decreases the sliding safety factor because of increase in the magnitude of horizontal forces and decreases bearing capacity safety factor because of increase in the magnitude of vertical forces acting on wall base.

5.3.2.2 Base length

Increasing the base length at a fixed value of heel enlarges toe length, which improves overturning safety factor by increasing the moment arms of resisting forces (Figure 5.1). The effect of change in overturning safety factor with the change in base length is independent of type of foundation soils (Figure 5.5). Sliding safety factor also increases slightly with the increase in base length (Figure 5.2). For cohesionless foundation soils, the effect of changing base length (holding heel constant) on the safety factor against wall sliding is not very significant as the raise in total vertical force (ΣV) is due to increase in weight of wall base only, which is small (Figure 5.7).

Some very interesting observations were made when studying the effect of change in base length on safety factor against bearing capacity failures. Lengthening the toe shifts the point of application of the resultant of forces acting on the wall base and alters eccentricity. The alteration in eccentricity affects the safety factor against bearing capacity failure. As can be seen from Figure 5.9 that the bearing capacity safety factor initially increases with the increase in base length because of a decrease in eccentricity and it attains maximum value at zero eccentricity. A further increase in base length reduces bearing capacity safety factor because of an increase in eccentricity. But when the base length becomes very large, the safety factor again increases because of large bearing area that diminishes the effect of eccentricity. The percent change in bearing capacity safety factor in cohesionless soils is almost twice as compared to the change in cohesive soils.

5.3.2.3 Heel length

Increasing the heel length at a constant base length improves safety factors against overturning and sliding because it increases the magnitude of resisting forces (Figure 5.6 and 5.8). The effect on the overturning safety factor is not as significant as on the sliding factor. The effect of increased heel on sliding safety factor is significant because of increase in soil weight over the heel which enhances the forces that resist wall sliding. The increase in soil weight over the heel also increases the magnitude of forces resisting overturning but the overall effect is

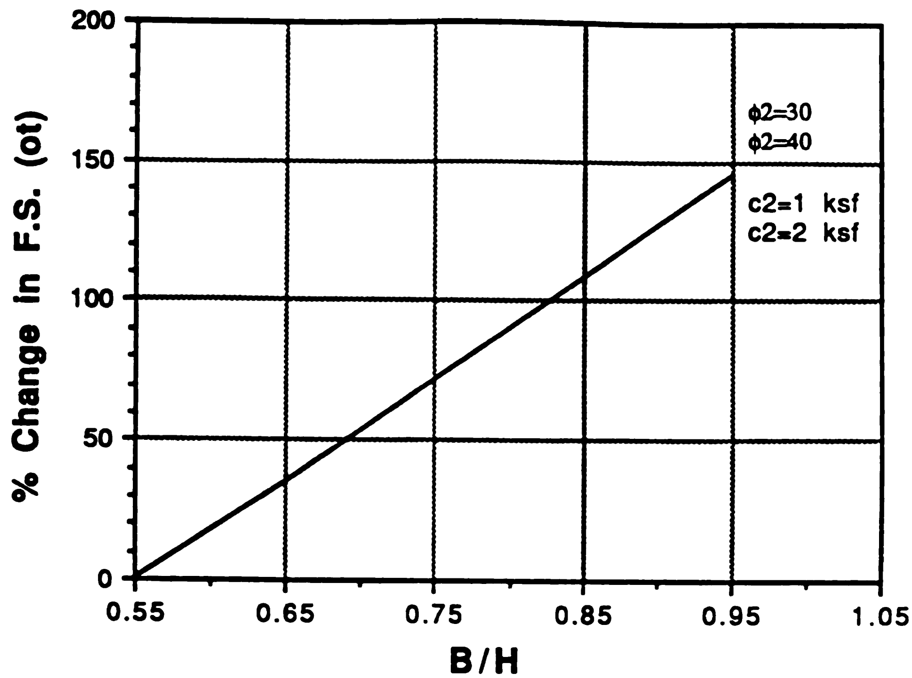


Figure 5.5 Effect of change in base length on overturning safety factor

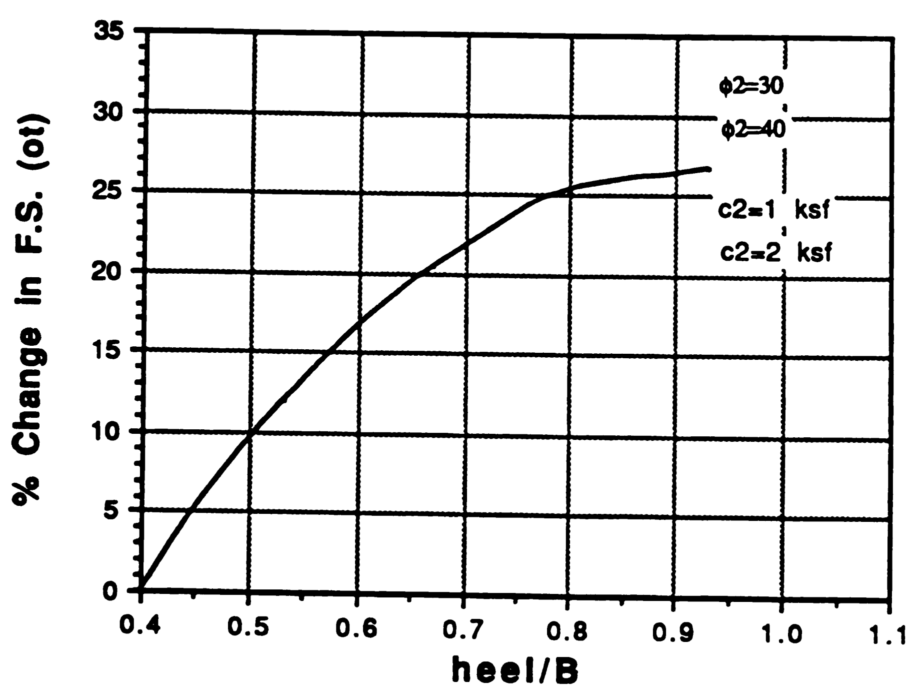


Figure 5.6 Effect of change in heel length on overturning safety factor

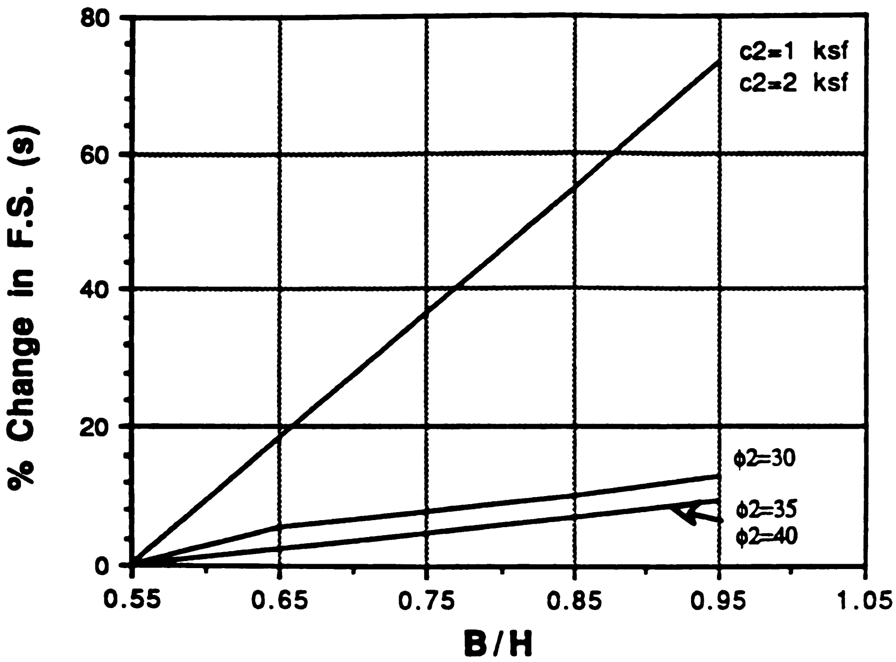


Figure 5.7 Effect of change in base length on sliding safety factor

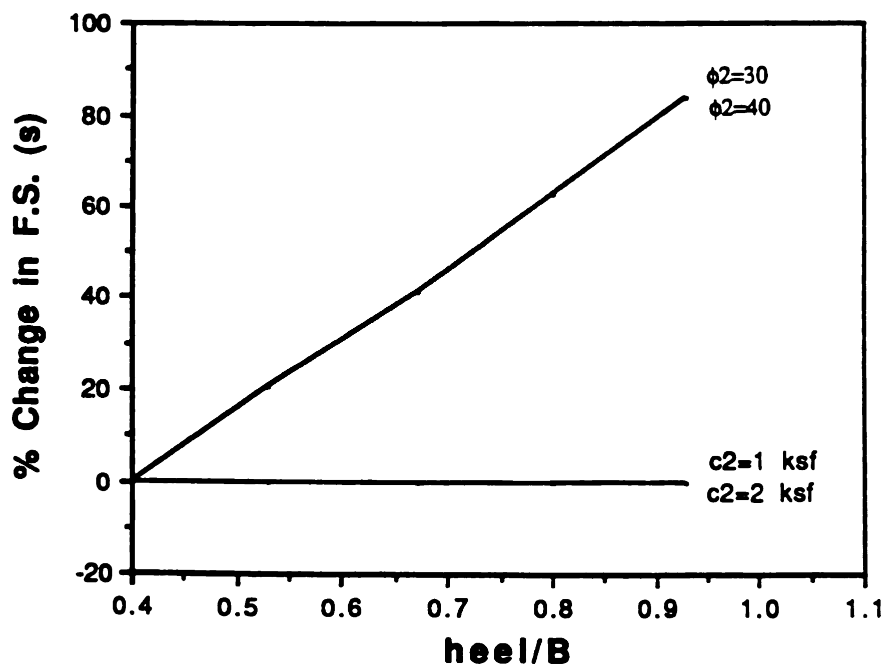


Figure 5.8 Effect of change in heel length on sliding safety factor

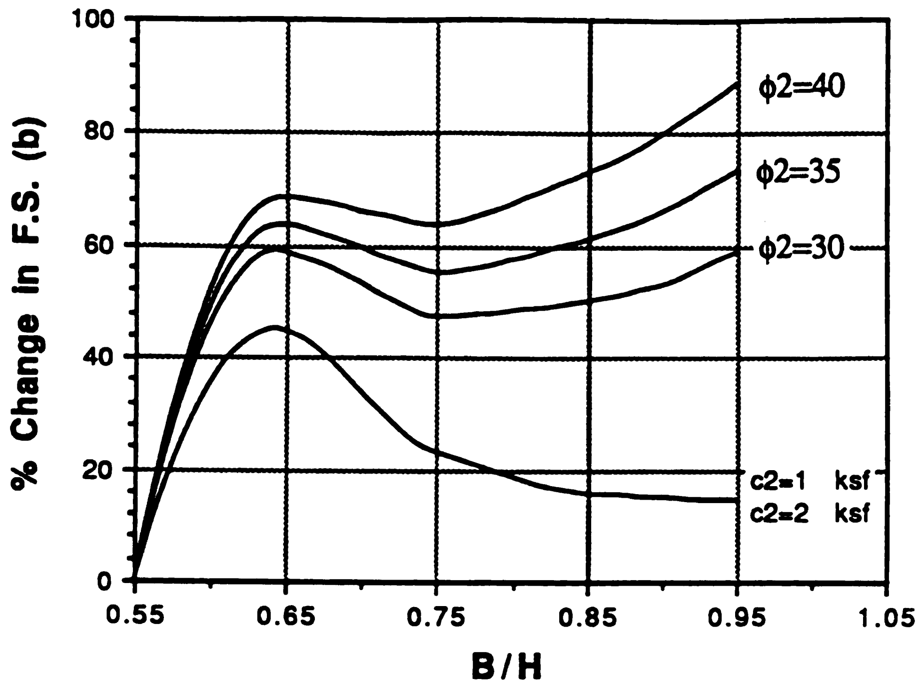


Figure 5.9 Effect of change in base length on bearing safety factor

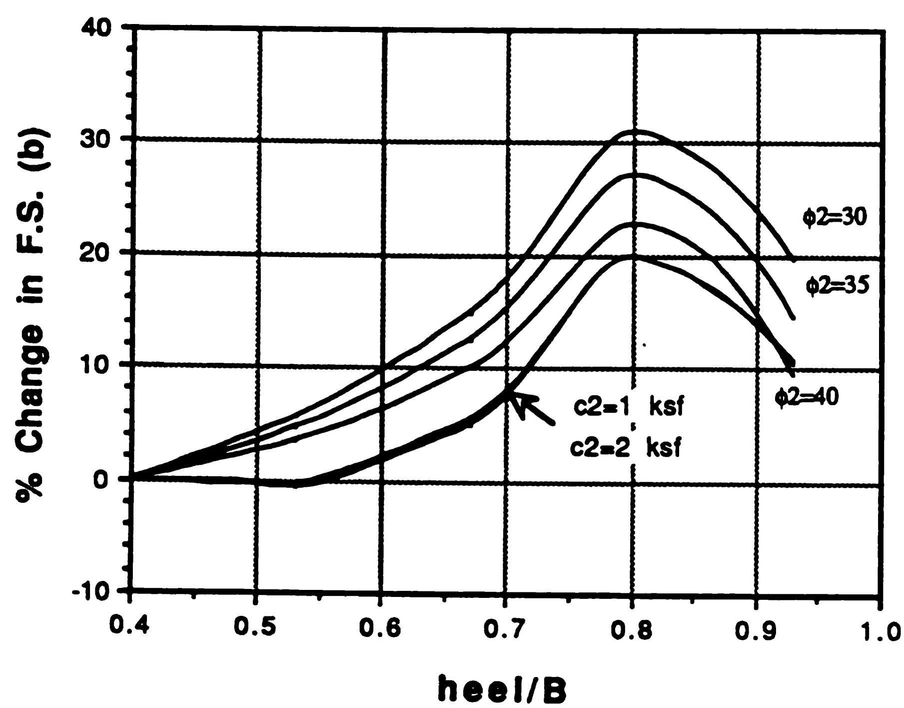


Figure 5.10 Effect of change in heel length on bearing safety factor

reduced because of reduction in the moment arm of resisting forces with decreased toe (toe length decreases when heel length is increased at constant base length). The change in heel length has no effect on the sliding safety factor in purely cohesive soils but it has a significant effect in cohesionless soils (Figure 5.8).

The effect of change in heel length on bearing capacity safety factor also resulted in some interesting observations. The variation of the bearing capacity safety factor with the change in heel length is shown in Figure 5.10. A change in heel length affects the location of the resultant of forces acting on the wall base and eccentricity, which in turn influences bearing capacity safety factor. The maximum safety factor was found to occur when the heel length is about 80 percent of the base length; and eccentricity corresponds to minimum value. The results suggest that in weak foundation soils, a large heel can help to improve bearing as well as sliding stability of the wall. But a large heel will also result in large bending moments at the intersection of heel stem which in turn will increase the requirement of steel. Thus, the designer has to keep in mind the economics of the design.

5.3.2.4 Backfill slope

Increasing the backfill slope angle β increases the coefficient of earth pressure and the height of vertical section at the end of the base. Therefore, the magnitude of the driving force P_{SD} is increased substantially. The effect of increase in vertical component of P_{SD} on wall stability due to increase in backfill slope is not sufficient to neutralize the effect of overall increase in P_{SD}. Thus, safety factors against overturning, sliding and bearing capacity failures decrease with the increase in backfill slope (Figure 5.1 to 5.3).

5.3.2.5 Soil Friction Angle

Increasing the backfill soil friction angle $\phi 1$ improves the safety factor against overturning, sliding and bearing capacity failures by reducing the driving forces (Figures 5.1 to 5.3). The increase in foundation soil friction angle has no effect on overturning safety factor (Figure 5.1) but it has significant effect on sliding safety factor (Figure 5.2). The foundation soil friction angle has marked influence on bearing capacity safety factor and the most significant change was observed when it was varied from 35 to 45 degrees (Figure 5.3).

5.3.2.6 Soil Unit Weight

The unit weight of backfill soil $\gamma 1$ has only a minimal effect and foundation soil unit weight $\gamma 2$ has no effect on safety factor against wall overturning and sliding. However, the increase in backfill unit weight decreases the safety factor against bearing capacity failure and the increase in unit weight of foundation soil increases the bearing capacity safety factor to some extent.

5.3.2.7 Wall Friction Angle

Increasing the assumed wall friction angle δ reduces the coefficient of earth pressure and horizontal forces and increases vertical forces on the wall. An increase in the $\delta/\phi 1$ ratio increases the safety factor against overturning and sliding and decreases the bearing capacity safety factor as shown in Figure 5.1, 5.2 and 5.3 respectively. The increase in overturning safety factor with the increase in wall friction angle is more pronounced at higher wall heights (Figure 5.11). The increase in sliding safety factor with the increase in wall friction angle is more pronounced at wall heights below 20 feet (Figure 5.12).

For a given wall height, the effect of wall friction on bearing capacity safety factor depends on eccentricity and the maximum safety factor is obtained when eccentricity is minimum. The effect of wall height on eccentricity at different values of wall friction angle is shown in Figure 5.13. The effect of wall friction on bearing safety factor at different wall heights is shown in Figure 5.14.

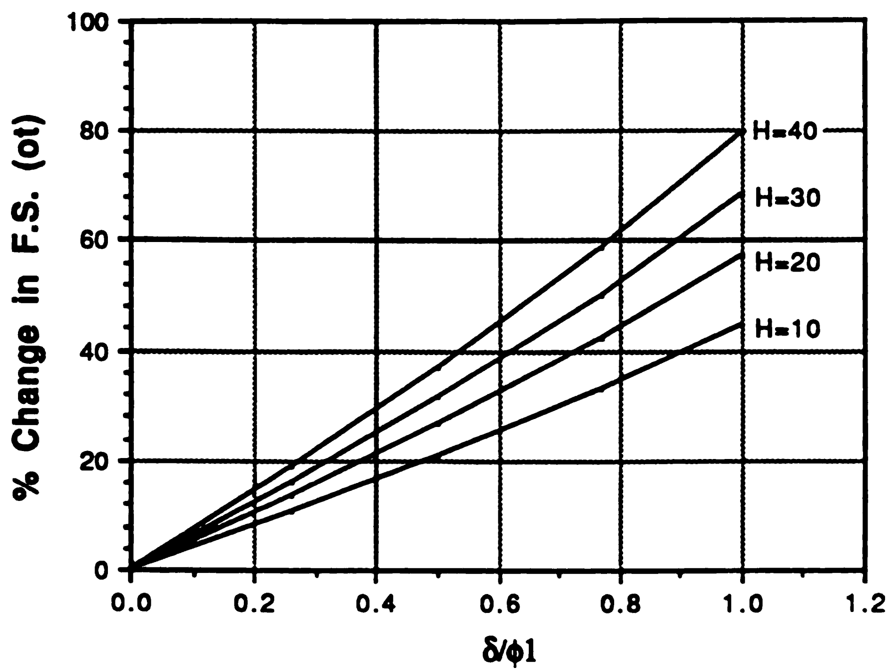


Figure 5.11 Effect of change in wall friction on overturning safety factor

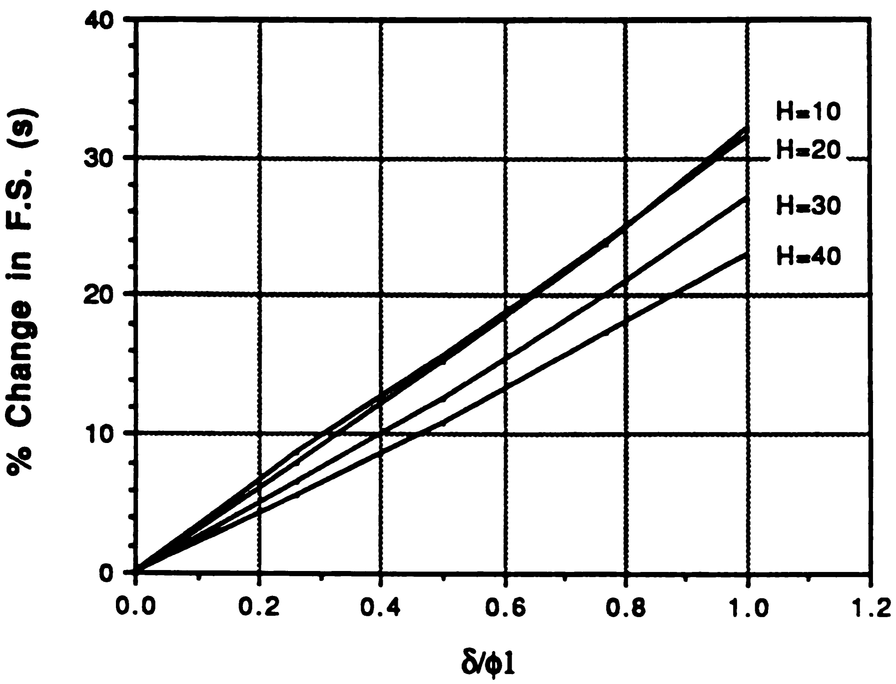


Figure 5.12 Effect of change in wall friction on sliding safety factor

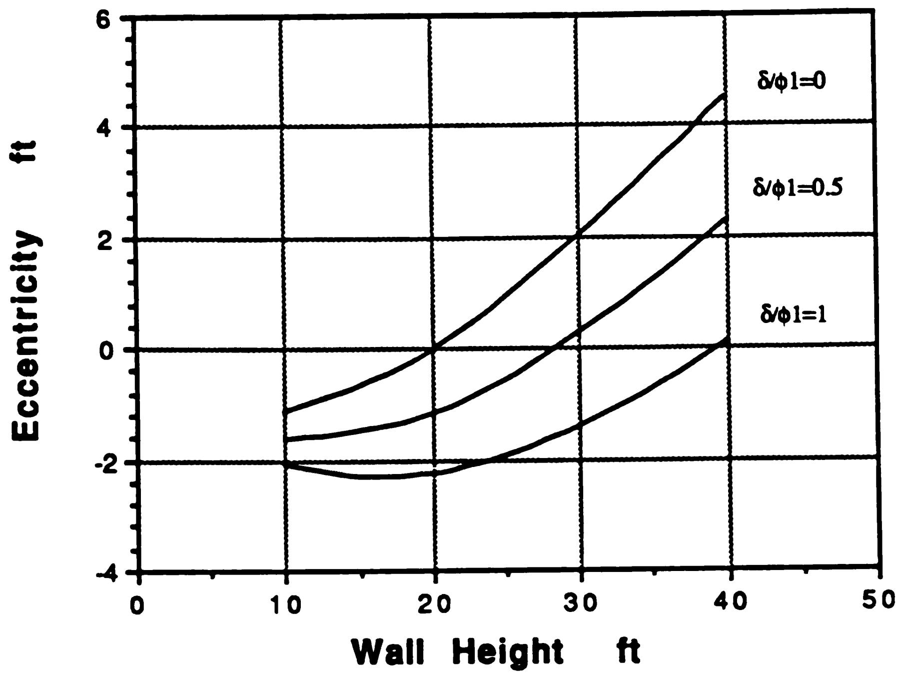


Figure 5.13 Effect of wall height on eccentricity at different wall friction angles

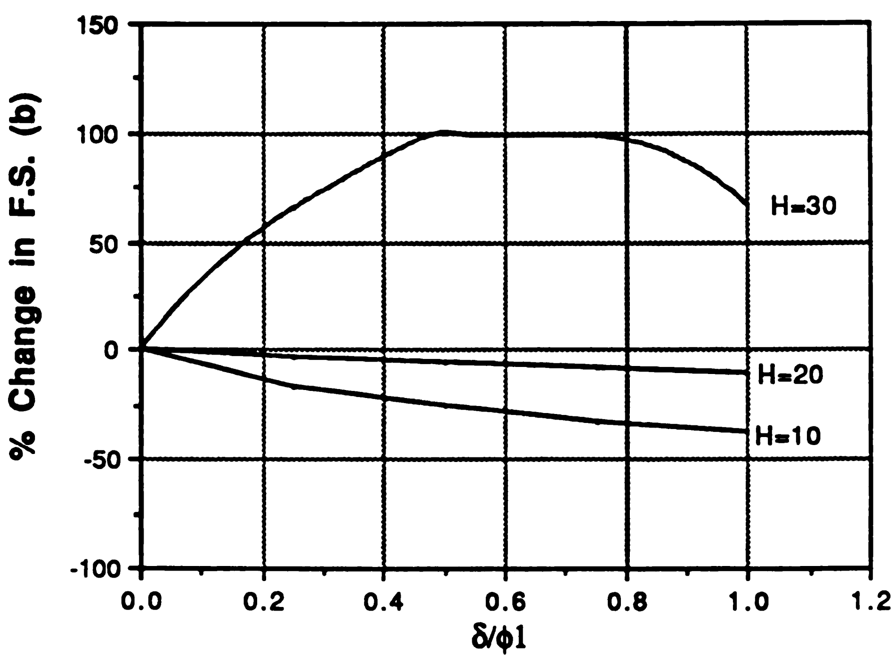


Figure 5.14 The effect of wall friction on bearing safety factor

5.4. Effect of Change in Heel Length on Pressure Distribution on Heel

5.4.1 General

Many references (Das 1984, Bowles, 1988) recommend a toe length of one-third of base length (i.e., heel length 40 to 50 percent of base length) but the reasons for this recommendation have not been well documented in the literature. A systematic approach has been followed in the present analysis to determine a maximum heel length or minimum toe length that can be used in the wall design without developing a net negative pressure on the heel (i.e., a case where the upward pressure beneath the heel at the intersection of heel and stem exceeds the downward pressure on the heel at that point).

An increase in heel length or decrease in toe length causes the point of application of resultant of forces on base to shift toward the free end of the heel; that increases the upward soil pressure at the intersection of heel and stem. The upward soil pressure at the point of intersection of heel and stem may become larger than the downward pressure at that point with an excessively long heel. Under such situations, a common assumption made for the structural design of heel (i.e., heel acts as cantilever beam and the point of maximum shear and moment is at the intersection of heel and stem) is violated. The wall design for moments and shears at the intersection of heel and stem may be unsafe under these conditions.

5.4.2 Method of analysis

Realistic values of backfill and foundation soil parameters were selected for this analysis (Figure 5.15). In this analysis, for a given wall height, the base length was established after optimizing the design. Then, the net downward pressure at the intersection of the heel and stem was computed for varying heel lengths between 50 to 70 percent of the base length. The analysis was performed by varying heel length because TWALL is structured to accept heel rather than toe as a trial dimension.

The analysis was first performed assuming horizontal backfill, neglecting wall friction and considering the water table at the wall base. Then, the effects of backfill slope, wall friction and water table on the distribution of pressure on heel were studied.

5.4.3 Results

In the present analysis, net downward pressure at the intersection of heel and stem was obtained by subtracting the upward soil pressure from the downward pressure at that point. The effect of change in heel length on net downward pressure at different wall heights is shown in Figure 5.15.

The figure shows that higher the wall height, the longer the heel that can be used without the upward pressure exceeding the downward pressure on the heel.

Thus, varying heel (or toe) according to wall height will not only improve wall stability but also reduce the cost of the wall by reducing wall dimensions. The permissible heel length (a heel length that can be used in the wall design such that upward pressure under the heel does not exceeds the downward pressure) as a function of wall height is shown in Fig. 5.16. The figure shows that the permissible heel length increases from 60 % to 64 % when wall height increase from 10 to 25 feet.

The effect of change in toe length on pressure distribution on heel is shown in Table 5.3. The required minimum toe length also increased from 0.18B to 0.23B when wall height was increased from 10 to 25 feet.

Figure 5.16 and Table 5.3 is applicable to walls with cohesionless horizontal backfills, frictionless backface and water table at the base level. Necessary adjustment are required to be made for wall friction, sloping backfills and water table as discussed in the sections below.

5.4.3.1 Wall friction

The effect of wall friction on pressure distribution beneath the heel of a 15 feet high wall is shown in Figure 5.17. The figure shows upward pressure exceeds the

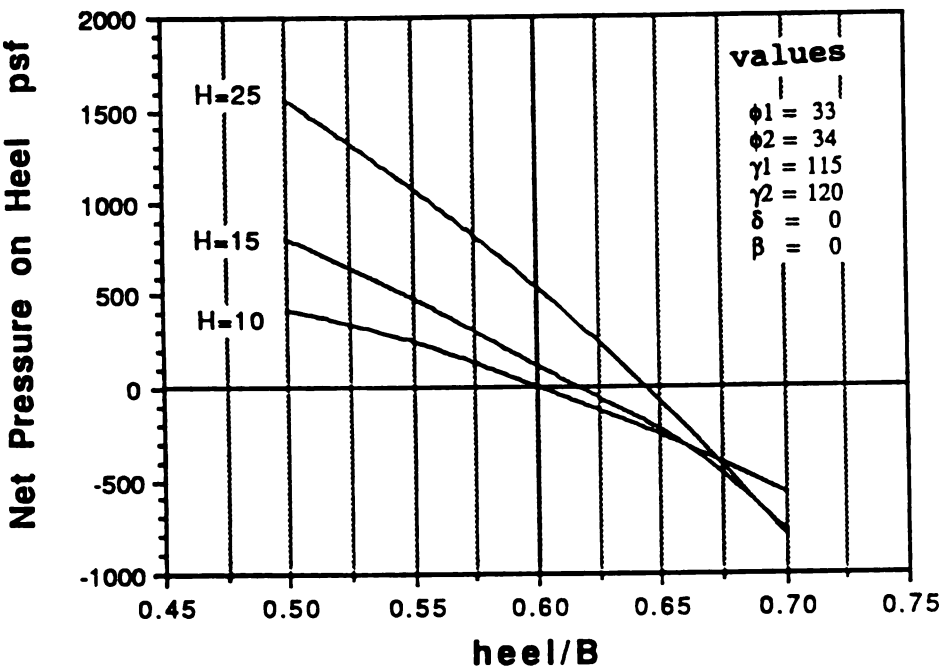


Figure 5.15 Effect of heel length on net downward pressure on heel at different wall heights

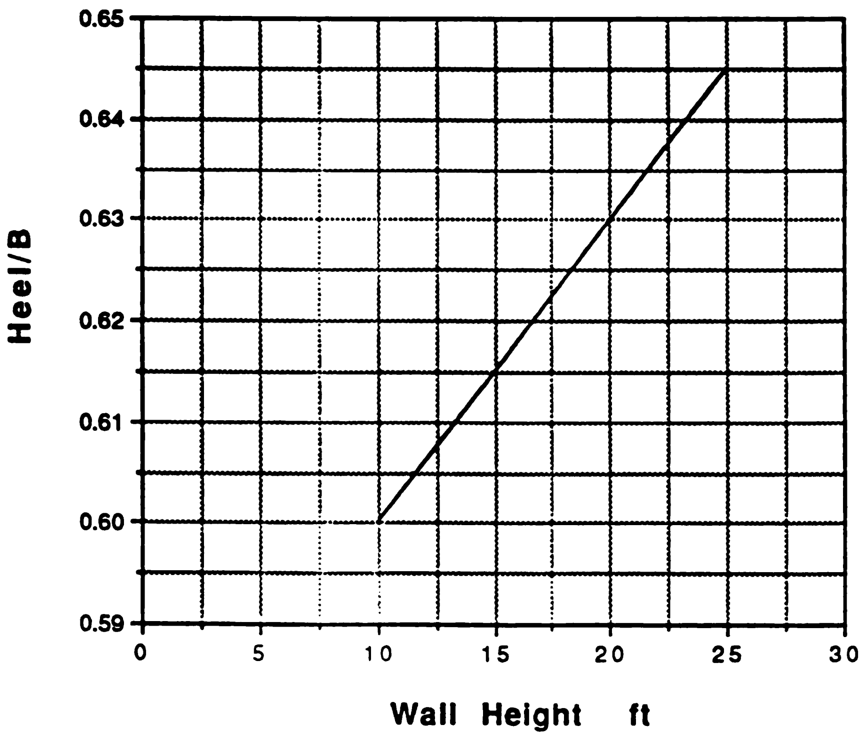


Figure 5.16 Effect of wall height on permissible heel length

Table 5.3 Effect of toe length on net pressure on heel at different wall heights

H ft	Toe ft	Toe/B	Toe/H	Net Pressure on Heel psf
10	1.56	0.280	0.16	433
	1.31	0.240	0.13	253
	1.01	**0.183**	0.10	10
	0.74	0.134	0.07	-257
	0.46	0.080	0.05	-575
15	2.46	0.328	0.16	810
	2.09	0.279	0.14	488
	1.71	**0.228**	0.11	123
	1.34	0.178	0.09	-229
	0.97	0.129	0.05	-775
25	4.35	0.334	0.17	1554
	3.70	0.284	0.15	1083
	3.05	**0.234**	0.12	548
	2.40	0.184	0.09	-71
	1.75	0.134	0.07	-795

Table 5.4 Effect of toe length on net pressure on heel at different wall friction angles (H=15 ft)

δ deg.	Toe ft	Toe/B	Toe/H	Net Pressure on Heel psf
$\delta=0$	2.56	0.328	0.16	810
	2.09	0.279	0.14	488
	1.71	**0.228**	0.11	123
	1.34	0.178	0.09	-229
	0.97	0.129	0.05	-775
$\delta=\phi/2$	2.01	0.335	0.134	737
	1.71	0.285	0.114	398
	1.41	**0.235**	0.094	19
	1.11	0.185	0.074	-413
	0.81	0.135	0.054	-908
$\delta=\phi$	2.01	0.335	0.134	418
	1.71	**0.285**	0.114	180
	1.41	0.235	0.094	-80
	1.11	0.185	0.074	-401
	0.80	0.135	0.054	-786

downward pressure at the intersection of heel at heel/B=0.62 when $\delta=0$ and at heel/B=0.53 when $\delta=\phi$. Thus, the wall friction significantly affects pressure distribution on the heel and reduces the heel length that can be used without developing a negative pressure on the heel. In the present case, the required reduction in heel length is about 14 percent when wall friction increases from $\delta=0$ to $\delta=\phi$. The permissible heel with the increase in wall friction angle is shown in Figure 5.18.

The effect of wall friction on toe length is shown in Table 5.4. The minimum required toe length increased from 0.23B to 0.29B when wall friction angle was increased from zero to soil friction angle. These limitations on toe generally agree with the recommendations (i.e., toe=0.33B) by Das (1984), Bowles (1988) but are based on observations.

5.4.3.2 Backfill Slope

In the present design, the total earth force is assumed to act parallel to the backfill slope. Therefore, backfill slope has a similar effect to that of wall friction (Figure 5.19).

5.4.3.3 Water Table

The effect of heel length on net pressure distribution at the intersection of heel and stem with different water

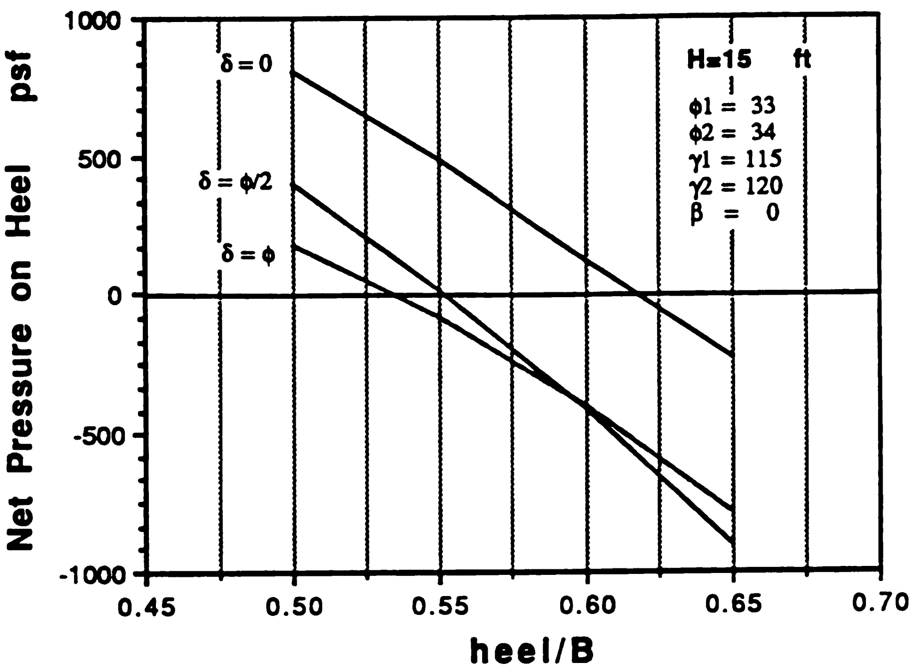


Figure 5.17 Effect of heel length on net pressure on heel at different wall friction angles

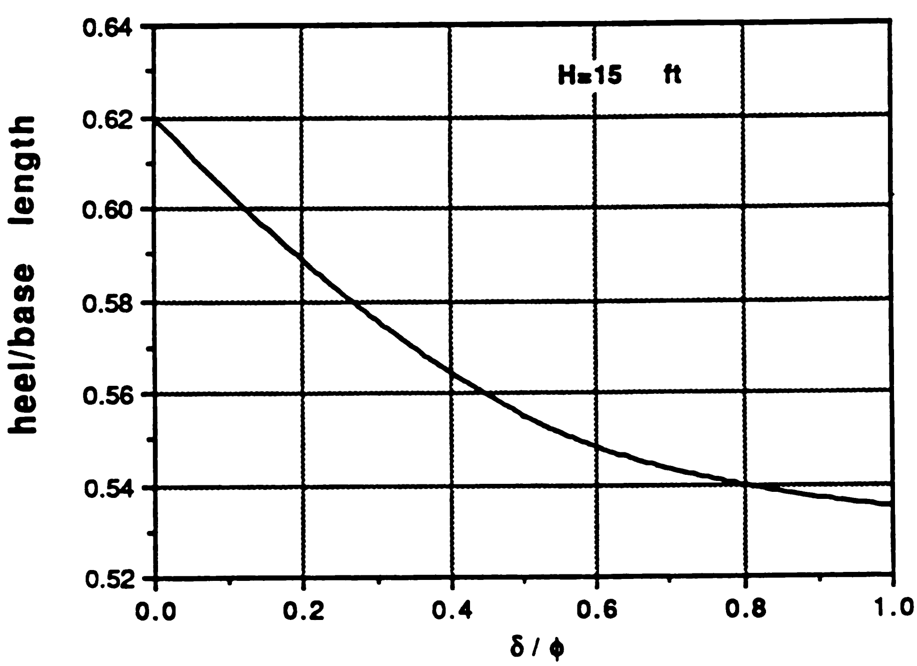


Figure 5.18 Effect of wall friction on permissible heel length

levels in the backfill behind a 15 feet high wall is shown in Figure 5.20. The water table on toe side was assumed at base level and the distribution of water and soil pressure under the base was assumed linear. The presence of water in the backfill increases downward pressure on the heel. The increase in upward pressure (soil and uplift) under the heel is not the same because of eccentric loading on the wall base. Therefore, net downward pressure on heel increases with the increase in water level in the backfill. Thus, a longer heel can be used for a given wall height with the presence of water in the backfill as compared to the heel length which can be used in the absence of water in the backfill (Figure 5.21).

6.4.4 Summary

The parametric sensitivity analyses discussed in this Chapter helped to understand the effects of different design parameters and wall proportions on the stability of the wall. Some useful heuristics were deduced from these analyses and were incorporated in TWALL to shorten the trial design process.

It was found from the second part of this analysis that the maximum heel length that can be used for the wall design without developing a situation when upward pressure under the heel exceeds the downward pressure may vary between 50 percent to 60 percent of base length. In other words,

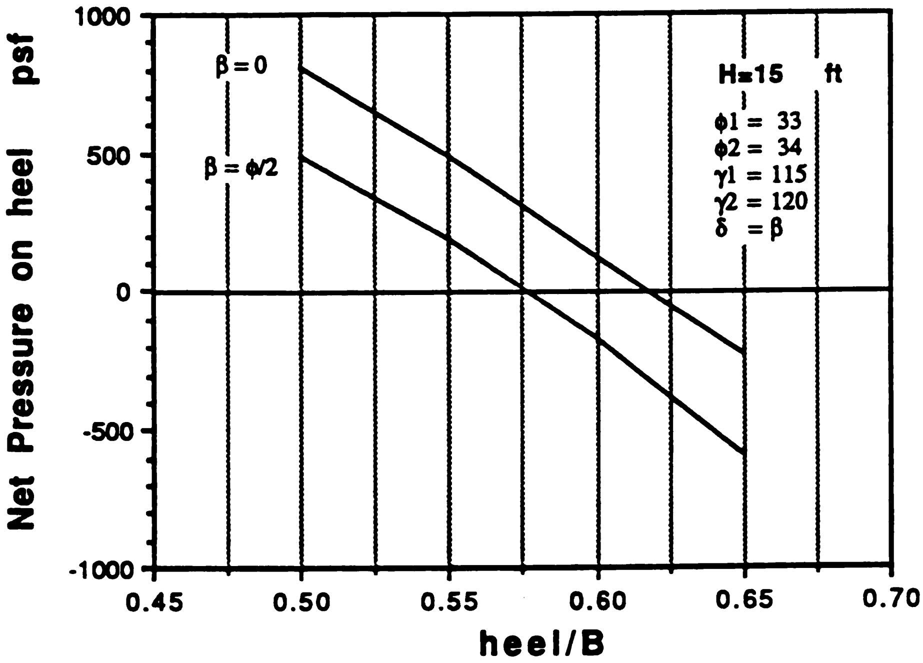


Figure 5.19 Effect of heel length on net pressure on heel at different backfill slopes.

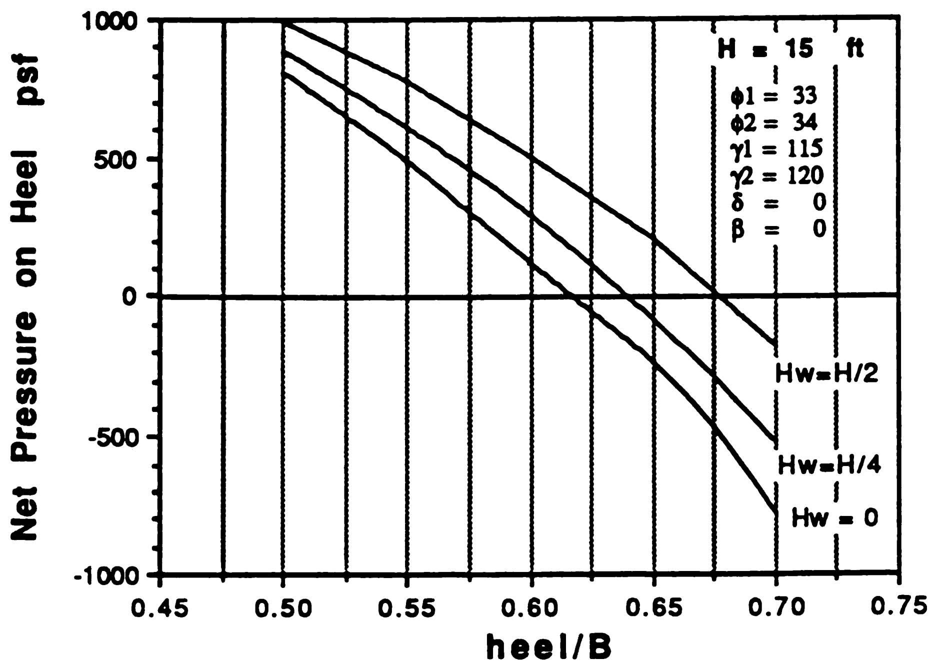


Figure 5.20 Effect of heel length on net pressure on heel at different water levels in backfill

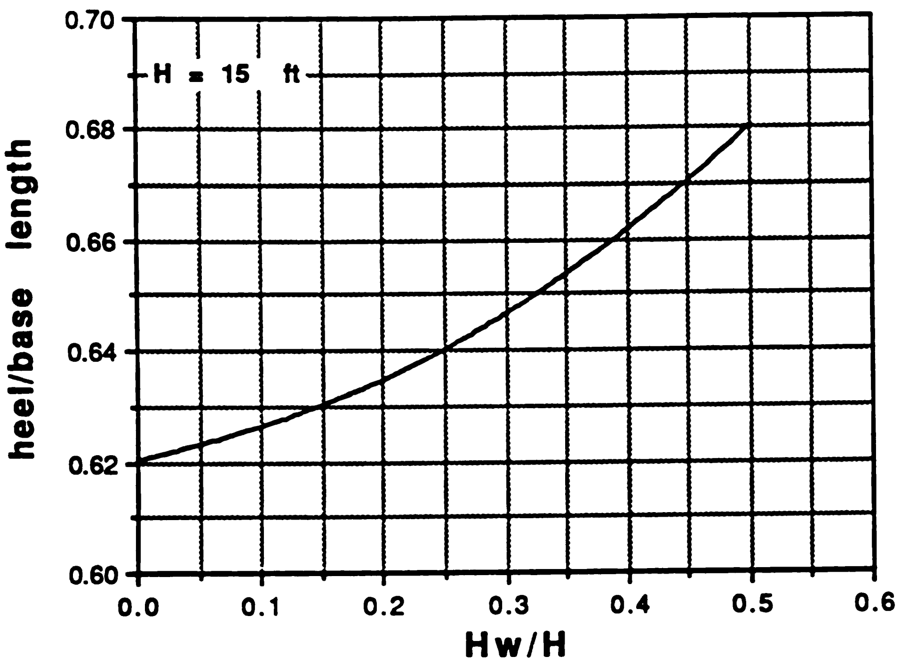


Figure 5.21 Effect of water table on permissible heel length

allowing 10 percent to 15 percent of the base length for stem, the minimum required toe length generally should not be less than 25 to 30 percent of the base length depending on wall height, backfill slope, wall friction and water table for a typical design of cantilever retaining walls.

CHAPTER 6

EFFECT OF EARTH PRESSURE ASSUMPTIONS ON WALL DESIGN

6.1 General

This chapter summarizes the results of an analysis performed to assess the difference between the assumptions of active and at-rest states of stress in the backfill on the design of cantilever retaining walls.

The design criteria for computing lateral earth pressures behind cantilever retaining walls are somewhat controversial. Some references (e.g., Das 1984, Bowles 1988) recommend assuming an active state of stress in the backfill for computing lateral earth pressures. On the other hand, some researchers (e.g., Matsuo et at., 1978) recommend assuming an at-rest state of stress in the backfill. U.S. Army, Corps of Engineer recommends assuming at-rest conditions in the backfill for overturning and bearing capacity analysis and active conditions for sliding stability analysis of the wall (U.S. Army 1989). The design assumptions regarding the state of stress in the backfill affect the magnitude of lateral earth force which ultimately affect recommended wall dimensions.

It was found from the literature review on cantilever wall design that no attempt has been made to quantify the effect of the assumed earth pressure conditions on wall dimensions, required quantities of materials and cost. The expert system TWALL provides a convenient and expedient means to investigate such questions. This analysis also helped in writing some heuristics.

A typical cantilever retaining wall (Figure 6.1) was analyzed to assess the effect of the earth pressure assumption on recommended base length, required quantity of backfill and concrete and cost per unit length of the wall. The effects of overload factors, wall friction, backfill slope and water table on overall cost of the wall under active and at-rest conditions were also studied. Coulomb and Jaky's equations were used for computing earth pressures for active and at-rest states respectively. The analysis is limited to cohesionless backfills and foundation soils not having settlement problems.

6.2 Method of Analysis

Realistic values of backfill and foundation soil parameters were selected as shown in Table 6.1. Means Building Construction Cost Data 1990 (Mahoney 1990) was used for calculating costs of cast-in-place concrete and compacted backfills. The analysis was performed in two parts.

In the first set of analyses, the wall height was

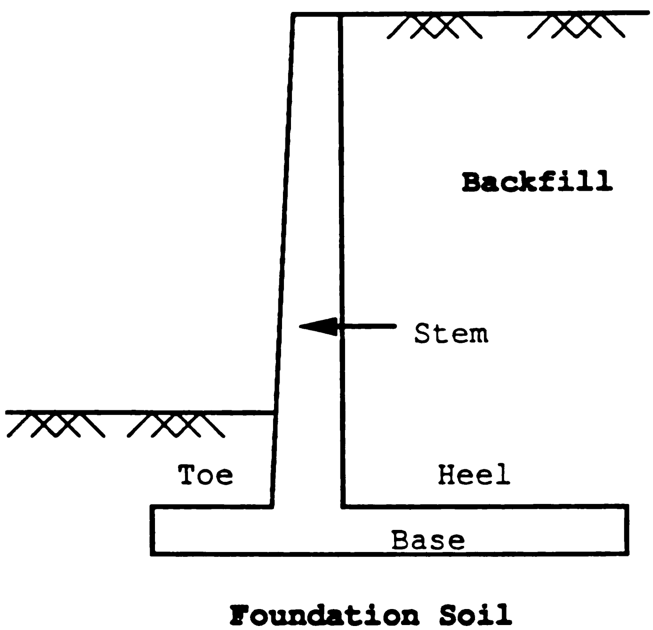


Figure 6.1 A typical cantilever retaining wall

varied from 10 to 30 feet for each assumption i.e., the active and at-rest. Using recommended base length from the expert system, required quantities of backfill, concrete and cost per lineal foot were computed. For these comparative analyses, the backfill was assumed horizontal, the water table was assumed at the base of the wall, wall friction was neglected and an overload factor of 1.7 was used for the structural design of stem, heel and toe.

In the second set of analyses, the effects of variation in parameters including overload factors, backfill slope and wall friction on wall design for active and at-rest assumptions were studied. These parameters were varied within the ranges shown in Table 6.1.

Table 6.1. Range of parameters

Parameters		Unit	Values
Backfill friction Angle	$\phi 1$	deg	34
Foundation soil friction angle	$\phi 2$	deg	35
Backfill unit weight	$\gamma 1$	pcf	115
Foundation soil unit weight	$\gamma 2$	pcf	120
Backfill slope angle	β	deg	0 - 0.75 $\phi 1$
Wall friction angle	δ	deg	0 - $\phi 1$
Load factor			1.4 - 2.0

6.3 Results

The results of the analyses are discussed in the following sections:

6.3.1 Part 1: Effect of Wall Height

The effects of wall height under different earth pressure conditions on required base length B, required quantities of material and overall cost per foot of wall were studied in this part. The results are shown first in terms of actual wall dimensions and quantities of construction materials (Figure 6.2 through 6.6) and then these results are summarized in term of percentages (Figure 6.7).

6.3.1.1 Base Length

The effect of wall height on required base length B for active and at-rest assumptions is shown in Figure 6.2. As would be expected, at-rest conditions result in greater recommended base lengths than the active conditions and the difference in required base lengths under these conditions increases with the increase in wall height. The required base length for at-rest conditions is about 39 percent higher than the required base length for active conditions (Figure 6.7). The variation of wall height does not affect this difference significantly.

6.3.1.2 Backfill and Concrete

The variation of required quantities of backfill and concrete per foot of wall as a function of wall height is shown in Figure 6.3 and 6.4 respectively. Backfill was calculated considering a unit wall length for the area above the heel to the ground level and the area of Coulomb's wedge at the end of the heel. The required quantities of backfill and concrete for both assumptions obviously increase with the increase in wall height. The increase is more rapid for high walls because the total earth force which is a function of the square of the wall height.

The difference in the required quantities of materials for wall heights below 10 feet is negligible but the difference increases with the increase in wall height. Possible (likely) reasons for this behavior are:

1. There are some minimum limits on wall dimensions for low walls (e.g., top stem thickness may not be less than 8 inches), which are not strength requirements but are rather for ease of construction (Bowles 1988). These restrictions on wall dimensions result in almost the same stem and base thicknesses for wall heights below 10 feet. Therefore, for low walls, the material requirements for both pressure are almost the same.
2. The increase in lateral earth force on the stem with increasing wall height is more rapid for an at-rest state of stress than for an active state of stress (Figure 6.5). The requirement of bottom stem thickness increases more rapidly with the

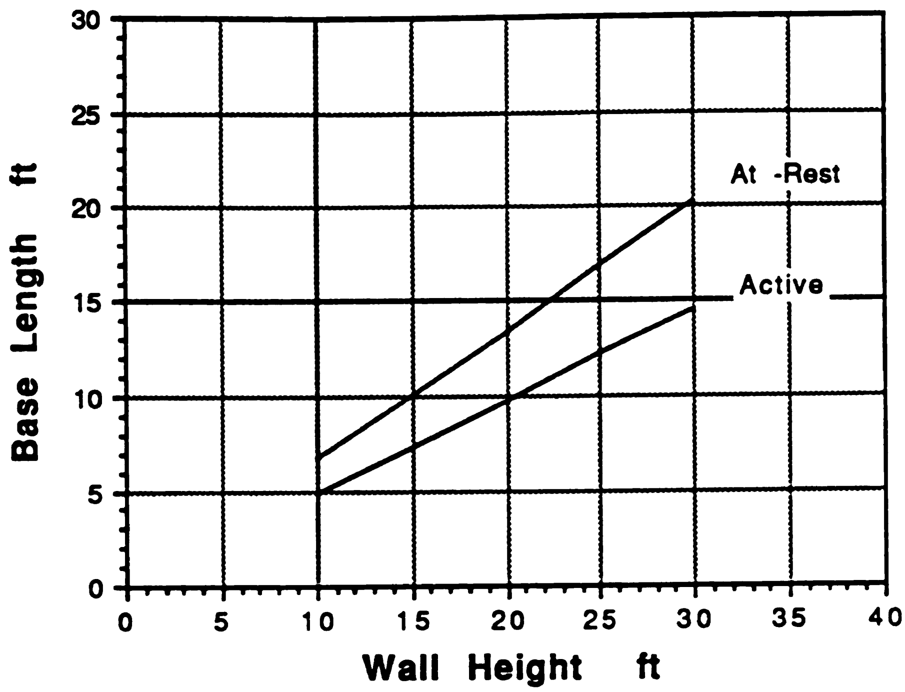


Figure 6.2 Effect of wall height on base length

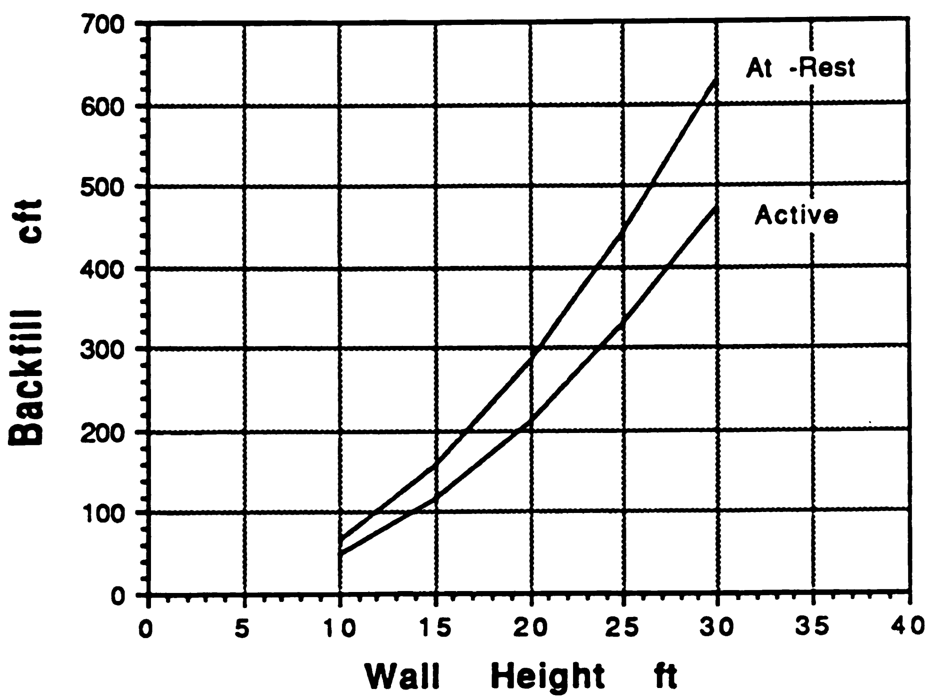


Figure 6.3 Effect of wall height on required backfill

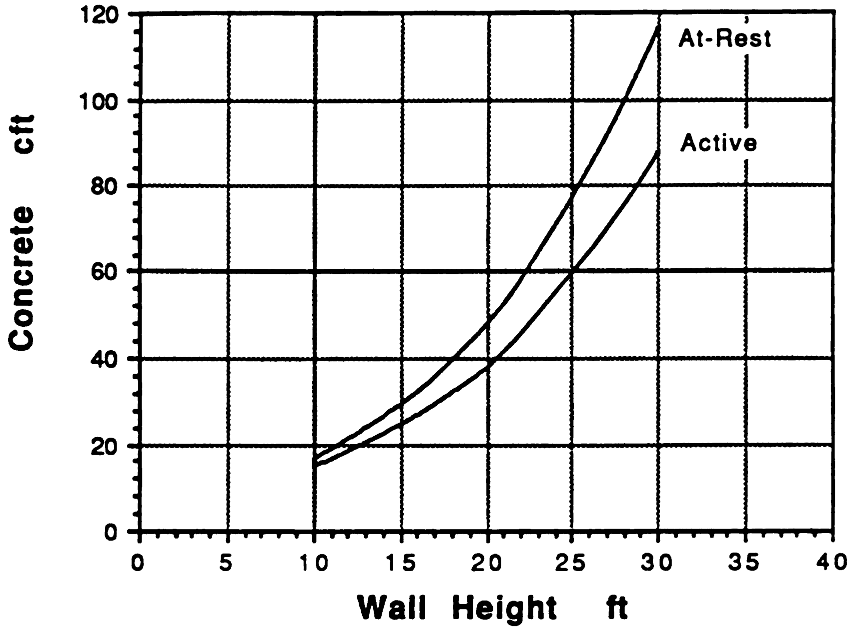


Figure 6.4 Effect wall height on required concrete

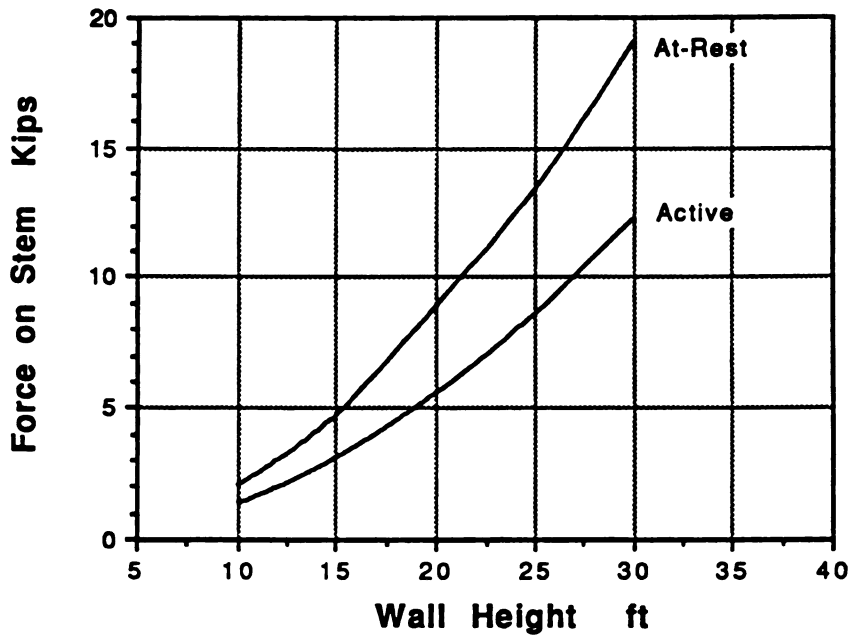


Figure 6.5 Effect of wall height on earth force on stem

increase in wall height for at-rest state than for active state. Thus, the required quantity of concrete increases more rapidly.

The ratio of required quantity of backfill for at-rest to that for active conditions decreases from 1.4 for H=10 feet to 1.34 for H=30 feet (Figure 6.7). This decrease is mainly due to variation in ratios of heel/B for different wall heights (i.e., same ratio of heel/B under active and at-rest conditions could not be used for all wall heights because of stability requirements). Thus, the required backfill for at-rest conditions is about 30 to 40 percent more than the active conditions.

The ratio of concrete required for at-rest versus active states increases with wall height (Figure 6.7). This increase can be attributed to a higher increase in the stem thickness under the at-rest state than the active state. As concrete is a more expensive construction material than the backfill, the effect of cost of concrete on total cost is more pronounced than the effect of backfill cost.

6.3.1.3 Wall Cost

The cost per linear foot of the wall increases with the increase in wall height for both active and at-rest conditions (Figure 6.6). The difference in the cost for the two assumptions is small for wall heights below 10 feet but the difference increases with increasing wall height. The cost per unit length of wall for at-rest assumption was observed to be about 17 percent to 34 percent higher than the active assumption when wall height was changed from 10 to 30 feet (Figure 6.7).

6.3.2 Part II: Other Factors Affecting Wall Cost

The effects of overload factors, wall friction assumption and backfill slope on cost per unit length of the wall were analyzed in this part of the analysis. The results are discussed in the following sections.

6.3.2.1 Effect of Overload Factors

The effect of overload factors on the cost at different wall heights for active conditions is shown in Figure 6.8. The effect is negligible for wall heights below 15 feet because of restrictions on minimum wall dimensions as discussed earlier. For wall heights between 20 to 25 feet, the cost per unit length of wall increased 9 to 15 percent when overload factors were increased from 1.4 to 2.0. The effect of overload factors on wall heights for at-rest conditions is shown in Figure 6.9. The results are almost identical to that discussed above.

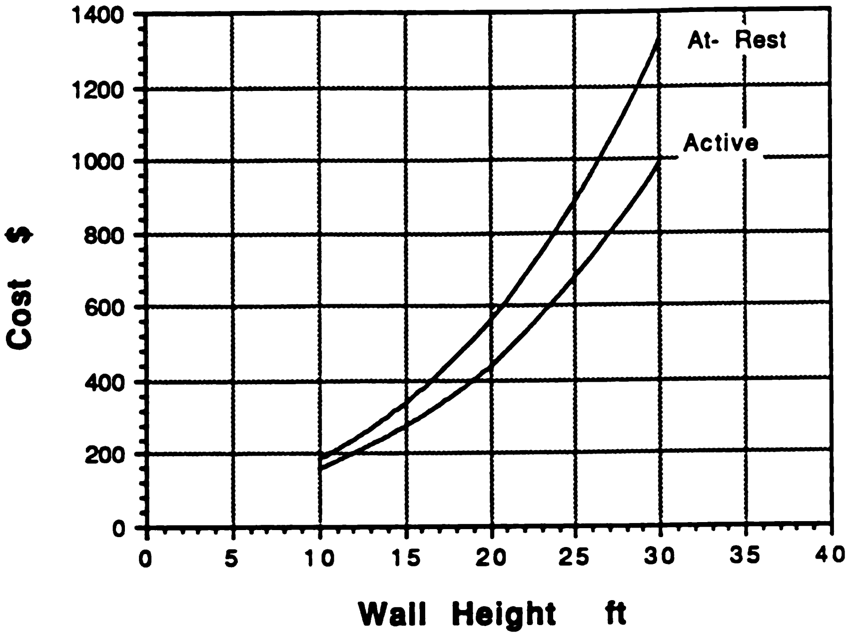


Figure 6.6 Effect of wall height on wall cost

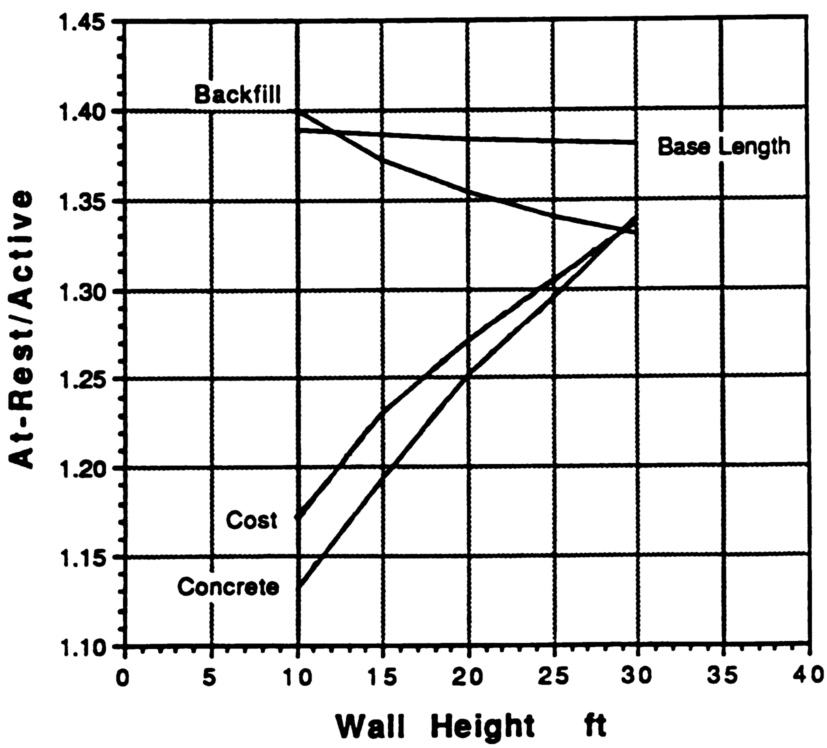


Figure 6.7 Difference in required materials and wall cost under active and at-rest conditions

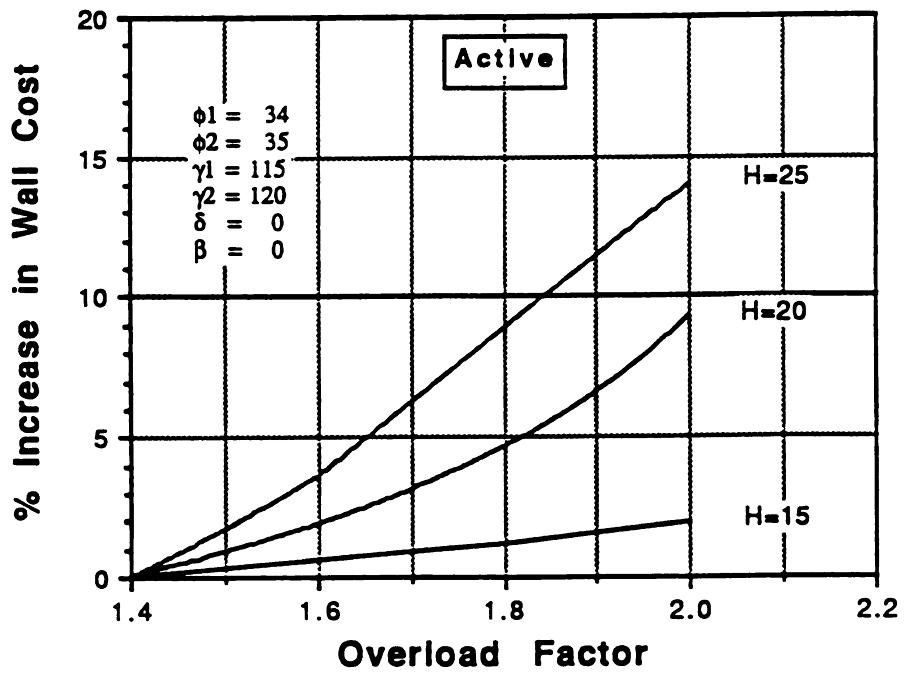


Figure 6.8 Effect of overload factors on wall cost assuming active conditions

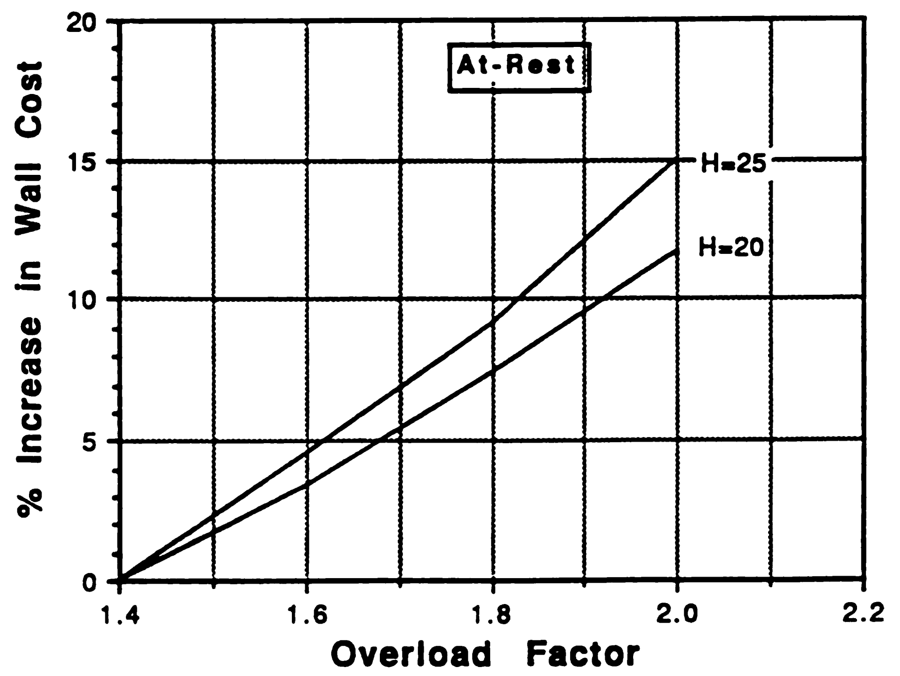


Figure 6.9 Effect of overload factors on wall cost assuming at-rest conditions

6.3.2.2 Effect of Wall Friction

An increase in wall friction angle decreases the cost of the wall (Figure 6.10). As can be seen from the figure, the decrease in wall cost as δ is varied from 0 to ϕ is about 10 percent for H=10 feet and 19 percent for H=30 feet. Thus, for high walls, the effect of wall friction on the cost of the wall is quite significant. The effect of wall friction on a 20 feet high wall for active and at-rest assumptions is shown in Figure 6.11. The figure shows that the decrease in the cost for the at-rest state is more rapid than the decrease for the active state.

6.3.2.3 Effect of Sloping Backfill

The effect of an upward sloping backfill behind a 20 feet high wall under active and at-rest states is shown in Figure 6.12. The upward sloping backfill substantially increases the cost of the wall. The increase in the cost is even more pronounced for the at-rest state of stress than the active state. The factors which contribute toward this significant increase in the cost include:

1. A high value of earth pressure coefficient which in turn increases lateral earth force on the wall. This results in larger wall dimensions which in turn increase quantity of backfill.
2. An additional quantity of backfill material for the

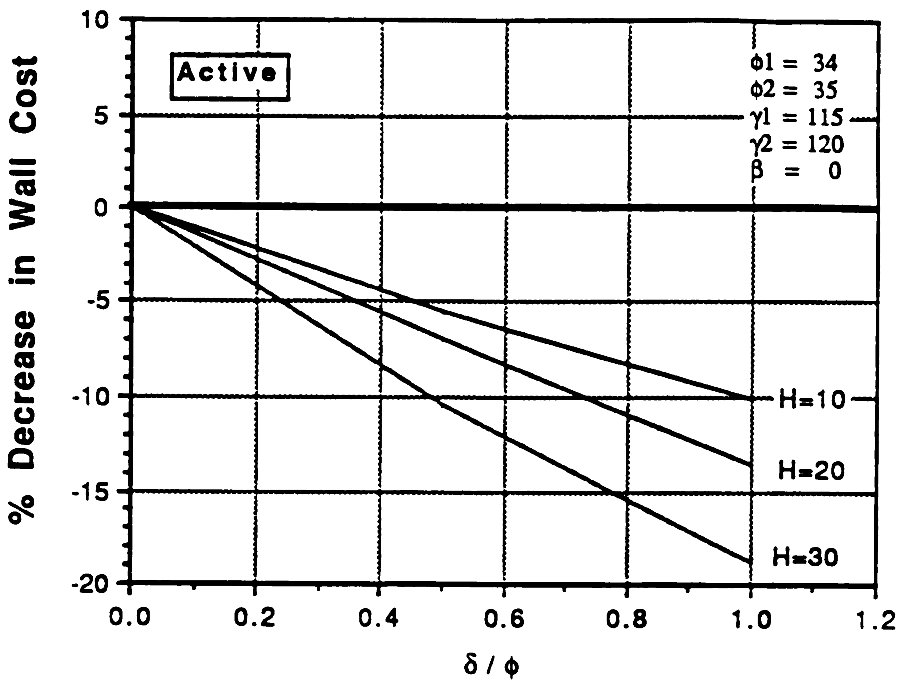


Figure 6.10 Effect of wall friction on wall cost for different wall heights

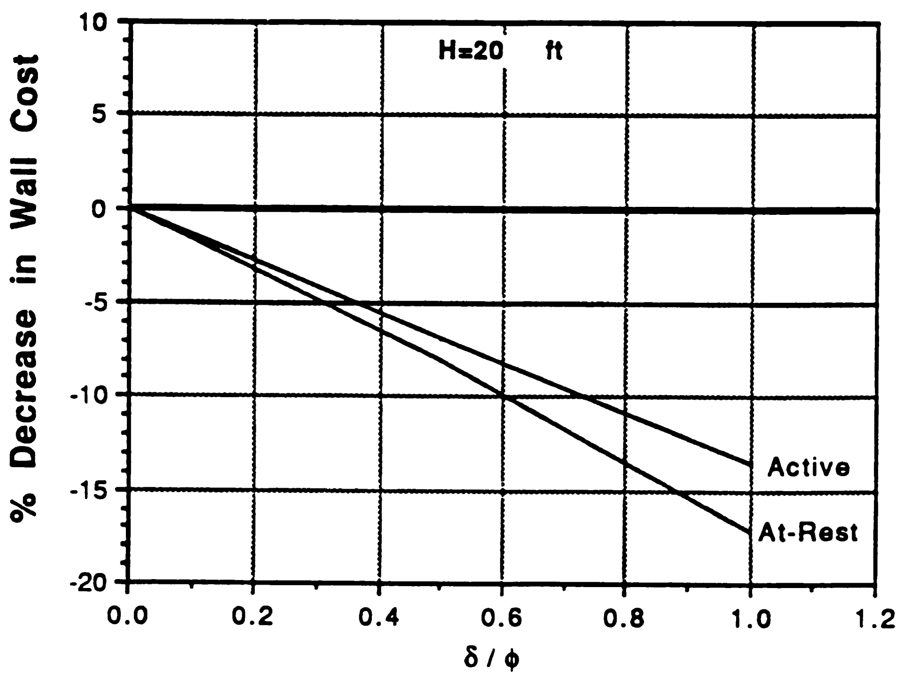


Figure 6.11 Effect of wall friction on wall cost assuming active and at-rest conditions

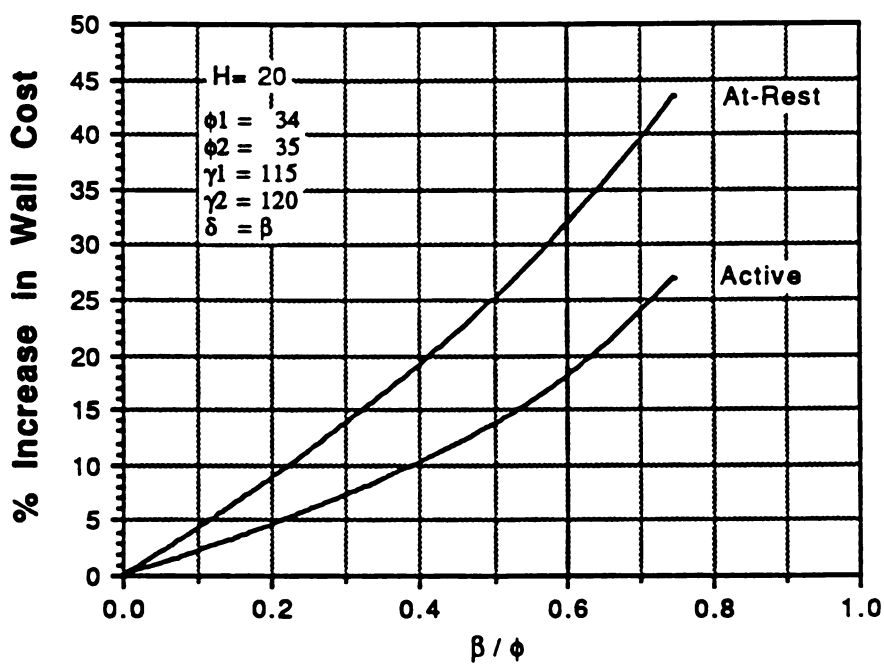


Figure 6.12 Effect of sloping backfill on wall cost

sloping part of the backfill.

3. The weight of sloping backfill on the heel which results in a thicker base thus increasing the requirement of concrete.

CHAPTER 7

KNOWLEDGE ELICITATION AND HEURISTIC DEVELOPMENT

7.1 General

The literature and human experts are the main sources of knowledge for the design of retaining structures. The knowledge obtained from the literature has been discussed in Chapter 2. The knowledge elicited from experts on the design of retaining structures is briefly discussed in this chapter. Some of the heuristic rules derived from literature review, experts knowledge, parametric sensitivity analysis and active versus at-rest analysis are also described. The heuristics developed through simulation and experimentation during the development of TWALL and discussed in Chapter 4 are also briefly repeated to complete the list.

7.2 Knowledge Elicitation

A detailed review of literature on earth retaining structures in general and cantilever retaining walls in particular was conducted. Standard textbooks, research papers and design manuals give sufficiently detailed information that can be used for the design of retaining structures. However, the information obtained from the literature lacks heuristic knowledge (e.g., what to do when a trial design fails in sliding) which is an essential requirement for building an expert system. Therefore, it was decided to consult human experts experienced in the design of retaining structures (engineers having geotechnical background and few years of experience in the design of retaining structures are considered experts in the present context). A questionnaire was prepared for this purpose addressing the following areas:

1. Heights for which cantilever walls are most suitable.
2. Initial trial dimensions of the wall.
3. Realistic ranges of design parameters.
4. Method to be used for earth pressure prediction.
5. Wall stability.
6. Structural design of stem, heel and toe.

Engineers involved with the design of earth retaining structures from both the public and private sectors were then invited to complete the questionnaire. Knowledge thus elicited was then organized and some heuristics were derived from this knowledge. The knowledge obtained was not quite agreeable among experts. Thus, a "middle" approach was used when writing heuristics. The results of the survey are summarized in Table 7.1 through 7.5.

7.3 Heuristic Development

The heuristics developed in this study are given below:

1. Cantilever retaining walls are most suitable for wall heights between 5 to 30 feet.
2. Maximum base length should not exceed twice the wall height.
3. Either the Coulomb or Rankine theory of earth pressure can be used for earth pressure prediction behind cantilever retaining walls.
4. Provided a reasonable safety factor is used the earth pressure distribution behind the wall can be assumed as hydrostatics and the point of application resultant earth force can be taken at 33 percent of wall height for the bottom of wall base.
5. The total horizontal force on the wall can be computed assuming active conditions behind the wall only when large wall movements are acceptable.
6. The effect of compaction can be incorporated in the design either by limiting the weight of roller or by taking the point of application of resultant of forces at 40 to 50 percent of wall height from

Table 7.1 Trial wall dimensions based on expert's opinion

Wall Parts	Miller et al. (1991)	Alvey (1991)	Gleason (1991)	Strom (1991)
Base				
Width (B)	0.67H Max=2H Min=12 in	0.8H Max=1.5H	0.75H Max=no limit	0.65H Max=H
Thickness	0.1 H Min= 12 in	0.15H	0.1H	0.15H
Heel length	0.5 B Min=12 in	0.5B	0.6B	0.45B
Stem				
Top thickness				
H < 10 ft	8 in	18 in	10 in	8 in
10 <H< 20 ft	12 to 24 in	24 in	10 to 18	12 in
H > 20 ft	0.1H	30 in	18+ in	12 in
Bottom thickness	0.1H	0.15H	0.1H	0.1H

H=wall height

Table 7.2 Expert's opinion on design values of soil parameters

Item	Miller et al. (1991)	Alvey (1991)	Strom (1991)	Bergstrom (1991)
Soil Friction Angle (degrees)				
1. Compacted Soil				
GW, SW	38	41	35	35
GP, SP	36	37	30	33
GW, SP	34	33	-	33
GC, SC	32	25	-	30
2. Loose Soil				
GW, SW	34	34	-	33
GP, SP	32	30	-	31
GW, SP	30	30	-	30
GC, SC	28	23	-	30
Soil Unit Weight (Pcf)				
1. Compacted Soil				
GW, SW	115-120	125	120	130
GP, SP	110-115	125	110	130
GW, SP	120-125	115	-	135
GC, SC	125-130	120	-	135
2. Loose Soil				
GW, SW	95-100	120	110	125
GP, SP	90-95	115	100	125
GW, SP	105	110	-	130
GC, SC	115	110	-	130
Wall friction angle	2/3 ϕ	2/3 ϕ	2/3 ϕ	2/3 ϕ
Friction angle between base and foundation soil	2/3 ϕ to ϕ	-	ϕ	ϕ

Table 7.3 Expert's opinion on earth pressure prediction

Item	Miller et al. (1991)	Alvey (1991)	Gleason (1991)	Strom (1991)	Bergstrom (1991
Appropriate Theory	Either Coulomb or Rankine	Either Coulomb or Rankine	Wedge method	Coulomb	Either Coulomb or Rankine
Pressure distribution	Hydrostatic	-	Hydrostatic	Hydrostatic	-
Point of application of resultant earth force	0.33H with reasonable safety factor	0.33H	0.33H	0.4H	0.33H
Compaction effect can be incorporated in design	By Assuming resultant at 0.4 to 0.45H	By limiting the weight of roller	By limiting weight of roller	Resultant at 0.4 to 0.5 H or at-rest conditions	use higher K, or assume resultant at 0.4 to 0.5H
Design the wall always for at-rest conditions	No	-	-	Yes	Don't use at-rest if wall is not rigid
Passive pressure Pp in front of the wall be considered in stability checks	Yes; but use higher safety factor	-	Usually neglected but not exceed 1/2 Pp	Use limit equilibrium method	Yes; but use higher safety factor
Condition to be assumed for computing total horizontal force for sliding stability	Always assume active conditions	-	-	Use limit equilibrium method with F.S.s=1.5	Use active if wall movement is acceptable

Table 7.4 Expert's opinion on cantilever wall stability

Item	Miller et al.	Alvey	Gleasson	Strom	Bergstrom (1991)

Table 7.4 Expert's opinion on cantilever wall stability

Item	Miller et al. (1991)	Alvey (1991)	Gleasson (1991)	Strom (1991)	Bergstrom (1991)
Minimum Required Safety Factor					
1. Wall overturning	1.5	1.5	Resultant in middle third of base	Resultant in middle third of base	1.5
2. Wall Sliding	1.1 to 1.5	1.3	1.5 to 2.0	1.5	1.5
3. Bearing Capacity	3.0	2.0	3.0	-	2.5
Methods for improving overturning stability of the wall	Lengthen heel Increase B Heavier base Heavier wall	Wide base Deeper imbedment	Change wall geometry	Lengthen base Consider vertical shear component	Increase toe length
Methods for improving sliding stability of the wall	Place a key under the base close to heel	Add base key Lengthen base	Use key Use better backfill Slope base upward in toe direction	Lengthen heel Use key Consider vertical shear component	Increase toe depth to increase passive resistance
Methods for improving bearing capacity of foundation soil	Widen base Densify foundation soil Use geogrid/-geotexile	Widen base Use piles	Change wall geometry	Widen base	Lengthen heel Deeper toe embedment
For Computing safety factor against bearing capacity failures	Use maximum pressure under the base	Use average base pressure	Use average base pressure	-	Use average base pressure

Table 7.5

I
Overload Facto
1. When base considered
Stem
Heel
Toe
2. When base not considere
Stem
Heel
Toe
Critical Sect
1. Moments
Stem
Heel
Toe
2. Shears
Stem
Heel
Toe
Provisions o

Table 7.5 Expert's opinion on various aspects of structural design

Item	Miller et al. (1991)	Gleasson (1991)	Strom (1991)
Overload Factors			
1. When base pressure is considered			
Stem	Active 1.7 At-rest 1.4	Active 1.9 At-rest 1.7	1.9
Heel	DL 1.4 LL 1.7	Active 1.9 At-rest 1.7	1.9
Toe	DL 1.4 Pressure 1.6	Active 1.9 At-rest 1.7	1.9
2. When base pressure is not considered			
Stem	1.7	same as above	-
Heel	1.7		-
Toe	1.7		-
Critical Sections			
1. Moments			
Stem	Base top	Base top	Base top
Heel	Face of Stem (heel side)	At center line of stem steel	At stem steel
Toe	Face of Stem (toe side)	Face of stem (toe side)	Face of stem (toe side)
2. Shears			
Stem	Base top	Distance "d" from base top	Base top
Heel	Face of stem	Face of stem	Distance "d" from stem face
Toe	Face of stem	Distance "d" from stem face	Distance "d" from stem face
Provisions of ACI 318-83	Adequate	Adequate except some load factors	Adequate but difficult to apply. Use constant load factors

the bottom of the base.

7. The passive resistance in front of the wall should be neglected in wall design.

8. The friction angle of good granular backfill used in retaining wall problems is often between 30 to 36 degrees and unit weight is often in the range of 100 to 115 pound per cubic foot.

9. The wall friction angle can be assumed between 0 to 66 percent of the backfill soil friction angle but may not be less than backfill slope.

10. The friction angle between the wall base and foundation soil can be taken same as foundation soil friction angle.

11. Wall stability can be ensured by providing the following safety factors:

    Overturning = 1.5 to 3 or keeping the resultant within the middle third of wall base

    Sliding = 1.3 to 2

    Bearing = 2.0 to 3.0

12. Lengthening the heel and toe improves wall stability against overturning failures but lengthening the toe improves overturning stability more effectively than the heel. The expressions given below can help to compute the required increase in base B and heel lengths when a trial design fails in overturning:

B = (1.15)B+B(F.S.otReq-F.S.otAval)/F.S.otAval

heel = (1.10)heel+heel(F.S.otReq-F.S.otAval)/
F.S.otAval

where F.S. otReq is required overturning safety factor and F.S.otAval is available safety factor.

13. Wall stability against sliding can be improved by increasing the heel length or by adding a base key. The expressions below can be used to compute the required increase in base B and heel lengths when a trial wall design fails in sliding.

B = (1.03)B+B(F.S.sReq-F.S.sAval)/F.S.sAval

heel = (1.07)heel+heel(F.S.sReq-F.S.sAval)/
F.S.sAval

where F.S.sReq is the required safety factor and F.S.sAval is the available safety factor against sliding failure.

14. The following expressions can help compute the required decrease in base and heel lengths to make the design economical when a trial wall design is conservative:

B = 0.95B-0.35B(F.S.sAval-F.S.sReq)/F.S.sAval

heel = 0.95B-0.40heel(F.S.sAval-F.S.sReq)/
F.S.sAval

15. A base key should not be used routinely in wall design but should only be used when required to satisfy the stability requirements which otherwise are difficult to achieve with reasonable wall dimensions.
16. To improve safety against bearing capacity failure, the following action can taken:
    - Lengthen wall base.
    - Densify the foundation soil or replace it with better soil.
    - Increase embedment depth.
    - Use piles.
17. For computing safety factor against bearing capacity failure use an average base pressure over a base width reduced for eccentricity as suggested by Meyerhof.
18. If eccentricity is sufficiently great as to put part of the base in tension (i.e., $e>B/6$) and the base resultant acts on the toe side of the base, an increase in heel length can reduce eccentricity.
19. If eccentricity is excessive as above, but the resultant acts on the heel side of the wall, decrease in heel length can reduce eccentricity.
20. Upward soil pressure under the base should not be neglected for the structural design of heel. Doing so is unnecessarily conservative.

21. As known from active versus at-rest analysis that varying overload factors does not greatly affect wall cost. Thus, it is reasonable to use a uniform overload factor of 1.9 for the structural design of stem, heel and toe when wall is designed for active conditions and 1.7 when wall is design for at-rest conditions.

22. The critical section for shears and moments for the structural design of stem, heel and toe can be taken at the intersection of stem and base, stem and heel, and stem and toe respectively.

CHAPTER 8

DETAILED SUMMARY AND CRITICAL ASSESSMENT

8.1 General

The development and testing of the knowledge-base system TWALL and the numerous parametric analyses performed in this study provided an opportunity to critically assess the philosophy and procedure of cantilever retaining wall design. This chapter critically assesses various design assumptions and discusses the effect of variations in design parameters on wall stability. The failure criteria that govern the design of the wall and the salient features of TWALL are also discussed.

8.2 Design Procedure

The design of a cantilever retaining wall involves recommending the base size and the position of stem on the base as well as thickness and reinforcing of stem, heel and toe such that a number of criteria are satisfied. At present no closed-form solutions exist to directly obtain design proportions for cantilever retaining walls; as such the design is a trial and error procedure.

This trial and error procedure can be expedited by assuming reasonable trial dimensions (i.e., base, heel and toe) and intelligently revising successive trial designs based on the results of the preceding trials. There are various guidelines available in the literature on trial dimensions as presented in Chapter 2. During the development and validation process, TWALL was used for the analyses summarized in Chapters 5 and 6 as well as for solving design problems given to undergraduate and graduate classes (Appendix D). From these experiences the preliminary trial wall dimensions given below were found to work well and are the writer's recommendations.

1. Base length B
   - a. B = 0.5 to 0.6H   when water is below base
   - b. B = 0.6 to 0.7H   when water is above base

2. Base thickness t_b
   - a. t_b = 1 ft   when $H<10$ ft
   - b. t_b = 1 to 2 ft   when $10<H<20$ ft
   - c. t_b = 2 to 3 ft   when $20<H<30$ ft

3. Heel length
   - a. Heel = 0.50 to 0.55B   when $H<15$ ft
   - b. Heel = 0.55 to 0.60B   when $H>15$ ft

4. Minimum toe length

a. toe = 0.24B when $H<15$ $0=<\delta<0.5\phi$

b. toe = 0.26B when $15<H<30$ and $\delta=0.5\phi$

c. toe = 0.30B when $15<H<30$ and $0.5\Phi<\delta<\phi$

5. Top Stem thickness t_s

t_s = 8 in when $H<10$ ft

t_s = 12 in when $10<H<20$ ft

t_s = 18 in when $H>20$ ft

The guidelines given above are consistent with published recommendations but have been further refined through parametric studies and knowledge elicited from experts on the wall design. The recommended trial base and heel lengths are based entirely on the experience of the writer during TWALL development.

8.3 Lateral Earth Pressure (Considerations and Assumptions)

The pressures and forces acting on a cantilever retaining wall are indeterminate to a significant degree because the available static equilibrium equations are not sufficient to solve for unknowns. To obtain a solution, some additional assumptions need to be made. For nonlinear materials such as soil, it is commonly assumed that a failure state exists along some surface and that the shear strength of the soil is fully mobilized along that surface. Then the equilibrium equations are solved with these assumptions. This approach is known as limit-equilibrium analysis.

The Coulomb and Rankine theories are examples of limit equilibrium methods. For the prediction of earth pressure behind a cantilever retaining wall neither Coulomb's nor Rankine's equations apply exactly because the back of this type of wall departs greatly from a plane surface. However, Rankine's theory can be used without significant error as the wall interference with the outer rupture surface is usually very small (see Figures 2.4 and 2.5).

The use of Coulomb's theory is clearly justifiable when inclination of resultant lateral earth force is parallel to the backfill slope. For this special case (and a vertical wall) Coulomb's formula yields the same solution as Rankine's. To the extent that the wall friction differs from the slope angle, the error in Coulomb theory lies in the assumption that the failure surface is a plane.

Either the Coulomb or the Rankine equation can be used for earth pressure prediction in TWALL. By default TWALL uses Coulomb's equation but the user has an option to change to Rankine's equation by assuming the wall friction angle equal to the backfill slope angle.

8.4 Active Versus At-Rest Pressures

There is a controversy over the appropriate assumptions (i.e., active or at-rest) for computing lateral earth pressure behind cantilever retaining walls. The justification usually given for assuming active conditions is that the wall yields sufficiently for active pressure conditions to develop before any failure takes place. The considerations to support designing for at-rest are: (1) higher pressures have been observed in the past during most of the experimental work and field tests, (2) the wall may not yield to meet the required deformations for active conditions because of its rigidity, and (3) even after active conditions are achieved (i.e., shear strength of the soil is fully mobilized), the pressures may increase with time to at-rest due to relaxation of the soil particles.

In the light of above controversy, it was considered of interest to study the effect of active versus at-rest assumptions on wall dimensions, required quantities of materials and the cost of the wall. In the past, it was difficult to perform such an analysis because there was no tool available such as TWALL that would provide consistent (and thus comparable) design and also be easy to use.

The results of the analysis showed that for at-rest conditions, the required base length and quantities of backfill were about 40% greater and required concrete was 13 to 35 % greater depending on the wall height (10 to 30 ft). The additional overall cost varied from 17 % for a 10 feet high wall to about 35 % for a 30 feet high wall. Concrete is an expensive construction material as compared to the backfill soils. Thus, variations in the cost of the wall closely follow variations in the required quantities of concrete.

The effect of overload factors, wall friction and backfill slope angle on the overall cost of the wall under active and at-rest conditions were also studied. The maximum difference in costs due to the effect of overload factors and wall friction angles varied between 3 to 5 % which is insignificant. But a notable difference in wall cost (about 17 % at $\beta=0.75\phi$) was observed with the variation of backfill slope angle (see Chapter 6 for details).

Classical earth pressure theories (i.e., Coulomb and Rankine's) do not account for the numerous uncertainties associated with the prediction of earth pressure. Although designing for at-rest conditions costs about 20 to 30 percent more than designing for active conditions, it still would appear justified to design yielding walls for at-rest conditions to ensure wall stability and good performance under adverse conditions. For non-yielding walls, in addition to designing for at-rest, a surficial surcharge of few hundred pounds per square foot might be assumed when calculating earth pressure or higher safety factors should be used to compensate for the uncertainties. TWALL provides an option to the user to a design wall for at-rest conditions and uses Jaky's equation to calculate earth pressure.

8.5 Wall Stability

The stability of a cantilever retaining wall is affected by a number of variables including wall height, backfill and foundation soil parameters, wall friction, backfill slope and water table. A designer with some experience in the design of earth retaining structures can easily guess the individual effect of any of these variables but it is difficult to predict the relative magnitude of effect of these variables on the stability of the wall.

A parametric sensitivity analyses were performed (see Chapter 5) to study the effect of these variables on overturning, sliding and bearing capacity safety factors. Some important results of this analysis are briefly discussed in the following sections.

8.5.1 Overturning Stability

The overturning safety factor is most sensitive to the wall height and least sensitive to the unit weight of the backfill soil. An upward sloping backfill adversely affects overturning stability because it increases the earth pressure on the wall.

Wall friction helps to improve overturning stability by reducing overturning moments and increasing the resisting moments. The reduction in overturning moments is due to a decrease in earth pressure coefficient, reflecting the earth force acting at an inclination to the wall. The increase in resisting moments is due to the downward vertical component of the lateral earth force. The effect of wall friction is more pronounced for higher wall because the vertical frictional component is greater and acts at the end of a longer heel.

Increasing the base length at a fixed heel length results in a lengthened toe which improves overturning stability due to an increase in the moment arm of the resisting forces. Increasing the heel length at a fixed base length has little effect on overturning stability because weights over the heel increase as toe length decreases and these effects tend to compensate.

8.5.2 Sliding Stability

The sliding safety factor is most sensitive to backfill and foundation soil friction angles and least sensitive to the backfill soil unit weight. Increasing the base length at a fixed heel length has an insignificant effect on sliding stability in cohesionless foundation soils because an increase in base length adds only a small dead weight to the effective vertical force.

Increasing the heel length at a fixed base length in cohesionless foundation soil has a more pronounced effect on sliding safety than on overturning stability. This is because the increase in heel length significantly increases dead weights over the heel which directly improves sliding stability but has little effect on overturning.

The effect of wall friction on sliding stability is similar to that on overturning stability as discussed earlier. Increasing the wall height decreases the effect of wall friction on sliding stability. For a constant wall friction angle, an increase in wall height increases the vertical component of the lateral earth force which can be a small portion of the total vertical force. Therefore, the overall increase in resisting force is not significant but the horizontal component of the lateral earth force increases with the square of the increase in wall height. Thus, the effect of wall friction decreases with the increase in wall height. From the above discussion, it can be concluded that the effects of wall friction are more significant for low walls than for high walls.

8.5.3 Bearing Capacity

The bearing capacity of a foundation soil is most sensitive to the friction angle of the foundation soil and least sensitive to the change in heel length. Sloping backfill and the location of water table also significantly effect the safety factor.

Some important observations were made when studying the effect of changes in base and heel lengths on bearing capacity safety factor. It is generally understood that the increase in base length should improve bearing capacity safety factor but it was found from the present analysis that a change in base length at a fixed heel length affects the point of application of resultant of forces acting on the base. In other words, eccentricity significantly affects the bearing capacity of the foundation soil.

The safety factor attains a maximum value at minimum eccentricity (i.e., the resultant acts close to the middle of the base) and decreases with further increase in base length. However, when base length becomes very large, the effect of eccentricity is nullified due to increase in bearing area. It was found that minimum eccentricity can be obtained by keeping the base length equal to about 65 percent of the wall height using approximately the same range of parameters as used in this study (Table 5.1).

When studying the effect of change in heel length at constant base length on the bearing capacity safety factor, it was found that increasing the heel length increased the bearing capacity safety factor until the heel length was about 80 percent of the base. Then the safety factor dropped off with further increase in heel length as the eccentricity become excessively negative. Here again the maximum safety factor was obtained when eccentricity was a minimum.

A study conducted by Peck et al., (1948) showed that, with a few exceptions, most walls failed due to misjudgment of foundation conditions rather than to incorrect assumption regarding the backfill pressure. Thus, the potential bearing capacity failure should also be given due importance in the wall design especially as optimization leads to narrower base and heel lengths.

8.5.4 What Governs Design?

What failure mode (overturning, sliding or bearing capacity failure) should govern the design of cantilever retaining wall and under what conditions? The exact answer to this question could not be found in the literature because there can be no mathematical solution for such an ill-defined problem that is influenced by a large number of variables. It has been generally said that wall sliding usually governs the design.

From the experience of TWALL development, some of the observations regarding the failure modes may prove to be a step forward in better understanding the interrelationship of design variables for cantilever retaining walls. Overturning was found to govern the design only when backfill soil is very weak as compared to the foundation soil. A wall may fail in overturning with a short toe or heavy surcharges because a short toe reduces the resisting moments and a heavy surcharge increases overturning moments due to the point of application of lateral earth force that acts higher than one-third of the wall height.

The bearing capacity may govern when a combination of adverse conditions (e.g., dense and steeply sloping upward backfill and presence of water) occur simultaneously. Such conditions can occur adjacent to dam spillways and other hydraulic structures. In all other cases, wall sliding mostly governs the design.

8.6 Development of TWALL

TWALL was developed for IBM-compatible personal computers in production rule language provided by the LEVEL5 expert system shell. The LEVEL5 is an expert system building environment with both forward and backward chaining control strategies. The backward chaining control strategy was used in TWALL because it was found convenient to work with such control strategy in LEVEL5.

Backward chaining is considered appropriate for problems with large input data and few goals (e.g., diagonistic problems and interpretation tasks). Design problems are considered open-ended problems because there can be many solutions of the same problem. Thus, the backward chaining has not heretofore been considered appropriate for design problems such as the design of cantilever retaining walls.

The knowledge base of TWALL was structured such that the goals were kept minimum and a large number of unknown facts (e.g., pressures and forces on wall) were made known. This could be accomplished through computations within the rules as the LEVEL5 supports all types of mathematical computations. Thus, the use of backward chaining control strategy did not pose any serious problem in the development of TWALL. From this experience, it can be said that backward chaining can be used for design problems by carefully structuring the knowledge base and using appropriate expert system building tool.

The knowledge base of TWALL consists of a total of 297 rules and these rules are further classified into 14 building blocks for ease of programming and understanding the logic. A building block performs a specific task and contains rules required to implement the intended task.

TWALL was developed in stages. Initially, a prototype was developed based on knowledge mostly obtained from the literature. Parametric sensitivity analysis was then performed to understand the behavior of the wall under different loading conditions and for writing of heuristic rules.

A questionnaire was also sent to experts on the design of retaining structures to obtain heuristic knowledge and further verify the heuristics deduced from the parametric sensitivity analysis. Some of the heuristics deduced from the parametric sensitivity analyses were further refined and quantified through experimentation during the expansion stage of TWALL development (see Chapter 4 for details). The prototype was then expanded by incorporating these heuristics in the rules of TWALL.

In the testing, verification and validation stage of TWALL development, the system was first tested and verified to check that the inference process is executing exactly as it was intended to. For this purpose, the system was run with simple examples to observe any crash or malfunctioning. Then for the validation of TWALL, some solved examples were selected from textbooks and design manuals and TWALL results were compared with these solutions. These results compared closely (see Chapter 3 for details).

Walls designed by students of undergraduate and graduate classes (CE 419 and CE 818) were also designed on TWALL and results were compared. The results also compared closely (see Appendix D).

8.7 TWALL Design Process

The knowledge base of TWALL is structured to design the wall for external stability only or for both external stability and internal stability. When designing a wall for external stability, TWALL ensures that the wall is stable against overturning, sliding and bearing capacity failures. TWALL also controls rotational settlements by keeping the resultant as close as possible to the middle of the base.

When designing a wall for both external and internal stability, TWALL first ensures external stability and then calculates shears and moments at five different points (free end, 1/4, 1/2, 3/4 and fixed end) along the stem, heel and toe. The stem, heel and toe are commonly designed as cantilever beams which implies that maximum shears and moments occur at the intersection points of stem, heel and toe. Thus, TWALL calculates steel requirements assuming that maximum moments occur at the intersection points. This approach is correct for the stem and toe because TWALL ensures that maximum shears and moments always occur at their intersection points.

Where the heel is relatively long (typically>0.7B), the upward pressure under the heel at the intersection with the stem exceeds the downward pressure at that point. This shifts the points of maximum shear and moment from the intersection toward the middle of heel. Under these conditions a heel designed for shear and moment at the intersection with the stem may be unconservative.

The heuristics incorporated in TWALL limit heel length such that the upward pressures do not exceed the downward pressures at the intersection of stem and heel. Thus, TWALL ensures that the points of maximum shear and moment always occur where heel joins the stem. It is not difficult in practice to design the heel for a maximum moment that occurs at a point other than the intersection point. But is not done in TWALL for two reasons: (1) the assumption that the heel acts as a cantilever beam is violated, and (2) a significant number of rules would need to be added to the knowledge base to calculate the maximum shears and moments on heel at a point other than the intersection point which would have made the knowledge base unnecessarily large. TWALL is a prototype expert system where an effort has been made to replicate an "expert" but the program still cannot be regarded as an "expert" who would have to anticipate every thing about the wall design.

8.8 TWALL Versus Algorithmic Programs

The main five features of an expert system that separates it from a conventional or algorithmic program were described in section 3.1. TWALL incorporates these features as discussed below:

1. The LEVEL5 expert system shell was used for the

development of TWALL. The knowledge base regarding cantilever wall design was incorporated in a set of LEVEL5 production rules to make a working expert system. Thus, the knowledge base (or rules) of TWALL can be manipulated independently from the control mechanism provided by LEVEL5.

2. The inference process of TWALL can be conveyed to the user through an explanation facility. Explanations of static queries (queries regarding the technical contents of the knowledge base) were incorporated during the development process of TWALL. For dynamic queries (queries regarding inference process) LEVEL5 provides explanations through "REPORT" system.
3. The knowledge base of TWALL is developed in production rule language which is very close to natural language. Therefore, the knowledge base of TWALL is more readable and understandable.
4. The inference mechanism of TWALL looks at the conclusions of all rules of the knowledge base in perusal of each goal and selects the applicable rule whose conclusion matches the goal. In this way TWALL searches a large amount of knowledge at each cycle rather than applying small amount of knowledge over many cycles.
5. The knowledge base of TWALL can be extended simply by adding a goal in the main rule. The additional rules can be added anywhere in the knowledge base because rules need not be in any order as statements in procedural programs.

Conventional computer programs (e.g., the Corps of Engineers TWDA) for cantilever retaining wall design having an open-form solution method and may make numerous iterations to automate the design. Therefore, these programs are calculation intensive and time consuming. The heuristics incorporated in TWALL reduce the number of iterations to a very few and thus, saves substantial computational time. On average, TWALL makes 3 to 4 iterations and takes less than a minute on XT microcomputers (8 MHz) to automate the design which is a significant step forward in software engineering. The heuristics used in TWALL can also be used in existing algorithmic cantilever retaining wall design programs with some minor modifications.

8.9 Expert Systems in Education

Computers have been used in the educational environment as a problem solving tool for over twenty years. Students have been taught to program in various programming languages or to use application programs. Good educational applications software should have a friendly interface, interactive features and graphic displays. Using conventional approaches, it requires a considerable time to develop such a software.

Recently, expert system technology has become a new tool in solving problems in various disciplines. In the past, the development of an expert system was difficult because AI specialists were often needed. The cost to develop a system for educational uses was not justified to many institutions. At present, expert system building tools (shells) are available commercially and run on low-cost microcomputers. Thus, using expert system in the educational environments is now justified for both the software development cost and the hardware cost. As an example, expert system technology is being used for teaching concrete mix design (Malasri et al., 1989).

8.9.1 Educational Features of TWALL

Programs such as TWALL appear to have application in teaching design, explaining design process or acting as a surrogate consultant. The knowledge base of TWALL is structured such that the user is first queried for the required design parameters and then the system proceeds with the design process. During the consultation session, the user can ask "WHY" a certain piece of information is required, and the system explains the logic by displaying the rule that is being pursued. If the user is not clear about the content of the query being made, the system provides an elaborate explanation of the query through the "EXPAND" statement. The ability to answer "WHY" questions and explaining the queries makes the logic used by the system apparent. The student can learn by asking the system questions as he or she would ask the teacher.

The design process of TWALL is interactive i.e., it keeps the user informed through various displays during the design process. For example, if the trial wall fails in overturning, it recommends the increase in wall dimensions, displays them to the user (see Appendix B) and gives an option to the user to either accept these recommended dimensions or change them if not satisfied. In this fashion, the user remains involved in the design process. Once the design process is complete, the user can check the reasoning process of the design through the "REPORT" system of LEVEL5.

CHAPTER 9

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

This dissertation has presented the development of TWALL, a knowledge-based expert system for the preliminary design of cantilever retaining walls. The design of a cantilever retaining wall includes proportioning the wall dimensions to ensure external stability and providing sufficient steel and concrete area to ensure internal stability. The developed system is structured to ensure external stability and, at the user's option, internal stability of the wall. The development stages of TWALL included knowledge collection from the literature, development of a prototype, parametric sensitivity analysis, knowledge elicitation from experts on wall design, development of heuristics, expansion of the developed prototype and testing and validation of the program. The present program is limited to cohesionless backfills and foundation soils not having significant settlement problems.

The system was developed for IBM-compatible personal computers in production rule language provided by the LEVEL5 expert system shell. There are a total of 297 rules used in the development of TWALL. These rules are further classified into 14 building blocks. The idea of using building blocks was to classify all the rules according to their intended uses. The developed system has a user-friendly interface and is semi-automated such that it can obtain a design within 3 to 4 trials. Its computational time is less than a minute on XT class microcomputers.

9.2 Conclusions

The objectives of the study have been achieved with the development of the knowledge based expert system TWALL and the following conclusions are drawn from this experience:

9.2.1 Conclusions Regarding Application of Expert System Technology

1. The development of TWALL demonstrates the viability of knowledge-based techniques as an effective problem solving tool for design tasks that combine heuristic knowledge and extensive computations such as the design of cantilever retaining walls.
2. In the process of developing TWALL, the approaches used for the collection and formalization of the knowledge, development of the prototype and finally the expansion of the developed prototype by incorporating heuristics

have proven successful. The same approach appears fruitful for similar design problems in civil engineering.

3. Carefully-selected expert system building tools such as LEVEL5 can be used to represent both heuristic knowledge and knowledge expressed as extensive mathematical formulas and algorithms.
4. Backward chaining control strategy can be used for design problems by carefully structuring the knowledge base and using an appropriate expert system building shell.
5. Knowledge collection and formalization is the lengthiest part of building an expert system. The collection of heuristic knowledge from domain experts is even more difficult because experts are reluctant to share their hard-earned knowledge with the developer of an expert system.
6. TWALL can be used in educational environments to check the reasonableness of cantilever retaining walls proportioned by students. Students can also learn about the design process of cantilever retaining wall using explanation facility of TWALL.

9.2.2 Conclusions Regarding Wall Design

1. Based on various parametric studies and testing and validation results, it can be concluded that TWALL

efficiently obtains designs consistent with published examples, experienced designers and students solutions.

2. Parametric sensitivity analyses helped to understand the effect of various design parameters on the stability of a cantilever retaining wall. It was found that a toe length less than 30 percent of the base length may result in a situation where the upward pressure under the base exceeds the downward pressure on heel at the intersection of heel and stem. For this case, the assumption that the heel acts as a cantilever beam is violated. This situation can be avoided by providing an adequate toe.
3. The cost of a wall designed for at-rest conditions was greater than one designed for the active state by 17 to 34 percent as wall height was varied from 10 to 30 feet.
4. The effect of change in overload factors from 1.4 to 2 on the cost of the wall was negligible for walls below 15 feet because of constructibility requirements. For walls between 20 to 30 feet, the additional cost varied between 9 to 15 percent.
5. Wall sliding usually governs the design of a cantilever retaining wall when typical safety factors of 2, 1.5 and 3 are used to ensure wall stability against overturning, sliding and bearing capacity failures respectively. Overturning governs the design only when the wall is designed with very weak backfills and a strong

foundation soil. The bearing capacity of the foundation soil may govern the design when the wall is designed with a dense and steep upward sloping backfill, when there is a weak foundation soil and/or the water table is near the ground surface.

6. The point of application of the resultant on the base significantly affects the bearing capacity of the foundation soil. Increasing base and heel lengths improve bearing capacity and the peak bearing value is obtained at minimum eccentricity. Further increasing the base and heel lengths decreases the bearing capacity safety factor but as the base becomes very long (B>0.75H), the bearing safety factor again increases due to large bearing area.

9.3 Recommendations for Future Research

The interdisciplinary nature of this research has raised many questions; some of them remained unanswered and become required avenues for future research. These include the study of models to represent uncertainty in KBES, fuzzy logic and its application to design problems in geotechnical engineering and the development of knowledge-based systems for a variety of tasks in geotechnical engineering. The following areas appear to offer the greatest potential for further research:

1. Further extension of the developed system to other

types of retaining structures including gravity retaining walls and reinforced earth walls.

2. Expansion of TWALL knowledge base to estimate shear strength parameters of backfill and foundation soil from standard penetration test (SPT) or cone penetrometer test results.
3. Development of a reliability-based design procedure for cantilever retaining walls implemented using an appropriate expert system building tool.
4. Further evaluation and verification of concepts presented in this study and techniques and heuristics used to develop TWALL; for example, the empirical algorithms developed to refine trial dimensions and improve overturning and sliding stability and the use of knowledge-based systems for reducing the gap between the state-of-the-art and the state-of-the-practice.

LIST OF REFERENCES

LIST OF REFERENCES

ACI 318-89, Building Code Requirements for Reinforced Concrete, in ACI Manual of Concrete Practice, 1990, Part 3, pp. 318/318R-1 to 318/318R-253.

Adams, T.M., Hendrickson, C., and Christiano, P. (1988). "An Expert System Architecture for Retaining Wall Design." Transportation Research Record 1187, pp. 1-8.

Adams, T.M., Christiano, P and Hendrickson, C. (1990). "A Knowledge Base for Retaining Wall Rehabilitation Design." Proc., Design and Performance of Earth Retaining Structures, ASCE, PP. 125-138.

Adeli, H. (1988). "Expert Systems in Construction and Structural Engineering." Chapman and Hall, New York, 1988, pp. 1-44.

Alvey, M. (1991). The U.S. Army Corps of Engineers Personal Communication.

Bang, S. (1985). "Active Earth Pressure Behind Retaining Walls." Journal of Geotechnical Engineering Division, ASCE, March, pp. 407-412.

Bang, S., and Hwang, S.I. (1986). "Transition of Active Lateral Earth Pressures Behind Retaining Walls." Computers and Geotechnique 2, pp. 219-238.

Barr, A., and Feigenbaum, E.A. (1981). The Handbook of Artificial Intelligence, William Kaufmann Inc., California.

Bergstrom, W.R. (1991). Wayne Disposal, Inc., Personal Communication.

Balzer, R., Erman, L.D., London, P. and William, C. (1980). "HEARSAY III: A Domain Independent Framework for Expert Systems." Proc., First Annual Conference on Artificial, pp. 108-110.

Boose, J. H. (1986). Expertise Transfer for Expert System Design, Elsevier, New York.

Bowles, J.E. (1982). Foundation Analysis and Design, Third Edition, McGraw-Hill, New York.

Bowles, J.E. (1988). Foundation Analysis and Design, Fourth Edition, McGraw-Hill, New York.

Brandl, H. (1987). "Retaining Walls and Other Restraining Structures." Ground Engineer's Reference Book, F.G. Bell, ed., Butterworth, Boston.

Broms, B.B., and Ingelson, I. (1971). "Earth pressure Against the Abutment of a Rigid Frame Bridge." Geotechnique, Vol. 21, No. 1, pp. 15-28.

Clocksin, W.F. and Mellish, C.S. (1981). Programming in PROLOG, Spinger-Verlag, New York.

Clough, G.W., and Duncan, J.M. (1971). "Finite Element Analysis of Retaining Wall Behavior." Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 97, No. SM 12. Dec., pp. 1657-1673.

Cordingely, E.S. (1989). "Knowledge Elicitation Techniques for Knowledge-Based Systems." in Knowledge Elicitation, Dan Diaper, ed., John Willy & Sons, New York.

Coyle, H.M., Bartoskwsitz, R.E., Milberger, L.J. (1972). "Field Measurements of Lateral Earth Pressures on a Cantilever Retaining Wall." Research Report no 169-2, Texas Transportation Institute, pp. 16-29.

Coyle, H.M., Bartoskewitz, R.E., Milberger, L.J., and Butler, H.D. (1974). "Field Measurements of Lateral Earth Pressures on a Cantilever Retaining Wall." Transportation Research Record 517.

Das, B.M. (1984). Principles of Foundation Engineering, PWS Engineering, Boston.

Danish Geotechnical Institute (1978). Code of Practice for Foundation Engineering, Danish Geotechnical Institute, Copenhagen, Denmark, Bulletin No 32, pp. 52.

Davis R., et al. (1981). "The Dipmeter Advisor: Interpretation of Geological Signals." Proc., Seventh IJCAI, pp. 846-849.

Duncan, J.M., Clough, W., and Ebeling, R.M. (1990). "Behavior and Design of Gravity Earth Retaining Structures." Proc., Design and Performance of Earth Retaining Structures, pp. 251-277.

Dym, C.L., Levitt, R.M. (1991). Knowledge-Based Systems in Engineering, McGraw-Hill, New York

Fang, Y-S, Ishibashi I. (1986). "Static Earth Pressures with Various Wall Movements." Journal of Geotechnical Engineering, ASCE, Vol. 112, No.3, March, pp. 317-333.

Feld, J. (1940). "Review of Pioneer Work in Earth Pressure Determination and Recommendation for Earth Pressure Evaluation." Proc., Highway Research Board, pp. 730-749.

Fenves, S. J., Maher, M. L., and Sriram, D. (1984). "Knowledge Base Expert Systems in Civil Engineering." Proc., Computing in Civil Engineering, pp. 248-257.

Fenves, S.J. (1986). "What is an Expert System." Proc., Expert Systems in Civil Engineering, C. Kostem and M.L. Maher, eds., pp. 1-6.

Ferguson, P.M., Breen, J.E., and Jirsa, J.O. (1988). Reinforced Concrete Fundamentals, 5th Edition, John Wiley, New York.

Finn, G.A., and Reinschmidt, K.F. (1986). "Expert System in an Engineering-Construction Firm." in Expert System in Civil Engineering, C. Kostem and M.L. Maher, eds., pp. 40-54.

Flemming, U. (1988). "Rule-Based Systems in Computer-Aided Architectural Design." in Expert Systems for Engineering Design, Academic Press, Inc., Boston, pp. 93-112.

Gasching, J., Reboh, R. and Reiter, J. (1981). "Development of a Knowledge-Based Systems for Water Resources Problem." SRI Project 1619, Stanford Research Institute International, California.

Gleason, S. (1991). Personal Communication.

Greenwell, M. (1988). Knowledge Engineering for Expert Systems, John Wiley & Sons, New York.

Gould, J.P. (1970). "Lateral Pressures on Rigid Permanent Structures." Proc., ASCE Specialty Conference on Lateral Stresses in the Ground and Design of Earth Retaining Structures, Cornel Univ., Ithaca, pp. 219-269.

Handy, R.L. (1985). "The Arch in Soil Arching." Journal of Geotechnical Engineering, ASCE, Mar., pp. 302-318

Hansen, J.B. (1953). "Earth Pressure Calculation, The Danish Technical Press, Copenhagen.

Hassoun M.N. (1985). Design of Reinforced Concrete Structures, PWS Engineering, Boston.

Harmon, P., and King, D. (1985). Artificial Intelligence in Business - Expert Systems, John Willy, New YorK.

Harr, M.E. (1977). Mechanics of Particulate Media - A Probabilistic Approach, McGraw-Hill, New York.

Hayes-Roth, F., Waterman, D.A., and Lenat, D.B (1983). Building Expert Systems, Adison-Wesley, Reading, MA.

Huang, M.S., et al. (1986). "Faulty Diagnosis of Hazardous Waste Incineration Facilities Using a Fuzzy Expert System." in Expert Systems in Civil Engineering, C.N. Kostem and M.L. Maher, eds., ASCE, New York, pp. 30-37.

Huntington, W.C. (1957). Earth Pressure and Retaining Walls, John Wiley and Sons Inc., New York.

Hutchinson, P. J., Rosenman, M. A., and Gero, S. G. (1987). "RETWALL: An Expert System for the Selection and Preliminary Design of Retaining Structures." Knowledge-Based Systems, Vol. 1, No. 1 , Butterworth & Co., pp. 11-23.

Jaky, J. (1944). "The Coefficient of Earth Pressure At-Rest." Journal, Society of Hungarian Architects and Engineers, Budapest, Hungary, pp. 355-358.

Jakobson, B. (1958). "On the Influence of Wall Movement on Earth Pressure." Proc., Brussels Conference on Earth Pressure Problems, Vol. 1, pp. 105.

James, R.G., and Bransby, P.L. (1970). "Experimental and Theoretical Investigations of a Passive Earth Pressure Problem." Geotechnique, Vol. 20, No. 1, pp. 17-37.

Kezdi, A. (1975). "Retaining Walls." Chapter 5, Foundation Engineering Handbook, H.F. Winterkorn and H-Y Fang, eds., Van Nostrand Reinhold, New York.

Kezdi, A. (1987). "Lateral Earth Pressure." Chapter 13, Ground Engineer's Reference Book, F.G., Bell, ed., Butterworth, New York.

Kostem, C.N. (1986). "Attributes and Characteristics of Expert System." Proc., Expert Systems in Civil Engineering, C. Kosten and M.L. Maher, pp. 30-39.

Kulikowski, C.A. (1989). "Knowledge Base Design and Construction: From Prototyping to Refinement." Topics in Expert System Design, G. Guida and C. Tasso, eds., Elsevier, New York, pp. 145-178.

Lambe, T.W., and Whitman, R.W. (1969). Soil Mechanics, SI Version, John Willy, New York.

Lee, I.K., and Herrington, J.R. (1972). "Effect of Wall Movement on Active and Passive Pressure." Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 98, NO. SM 6, June, pp. 625-639.

LEVEL5 (1989). LEVEL5 User Manual, Information Builders Inc., New York.

Ludvigsen, P.J., Grenney, W.J., Dyreson, D., and Ferrara, J.M., (1986). "Expert system Tools for Civil Engineering Applications." Proc., Expert Systems in Civil Engineering, C. Kosten and M.L. Maher, eds., ASCE, pp. 18-29.

Maher, M.L. (1986). "Problem Solving Using Expert System Techniques." Proc., Expert Systems in Civil Engineering, C. Kostem and M. L. Maher ASCE, pp. 7-17.

Maher, M.L., and Allen, R. (1987). "Expert System Components." in Expert Systems for Civil Engineers, M.L. Maher, ed., ASCE, New York, pp. 3-14.

Maher, M.L. (1988). "HI-RISE: An Expert System for the Preliminary Structural Design." in Expert Systems for Engineering Design, M.D. Rychener, ed., Academic Press, Inc Bostan, pp. 37-53.

Maher, M.L., Fenves, S.J., and Garrett, J.H. (1988). "Expert Systems for Structural Design." in Expert Systems in Construction and Structural Engineering, Chapman and Hall, New York, pp. 86-121.

Mahoney, W.D., ed., (1990). Means Building Construction Data 1990, R.S Means Company Inc. Kingston.

Malasri, S., and Maldonado, S., (1989). "An Expert System for Teaching Concrete Mix Design." in Computers and Education, Vol. 13, No. 1, Pergamon Press, New York, pp. 69-76.

Matsuo, M., Kenmochi, S., and Yagi, H., (1978). "Experimental Study on Earth Pressure on Retaining Wall by Field Tests." Soil and Foundation, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 18, No.3, Sep., pp. 26-41.

McCormac, J.C. (1986). Design of Reinfored Concrete, 2nd Edition, Happer and Row, New York.

McGee, B. (1990). "The Representation and Use of Knowledge." in Understanding Knowledge Engineering, M. Mctear and T. Anderson, eds., Ellis Horwood, Chinster, England. pp. 69-93.

Miller, K.C., et al. (1991). American Electric Power Service Corporation, Personal Communication.

CBEAR (1982). Computer Program for the Bearing Capacity Analysis of Shallow Foundation by R.L. Mosher and Pace and M.E. Pace. Instruction Report K-82-7, US Army Waterways Experiment Station, Vicksburg.

Mullarkey, P.W. (1985). "CONE: An Expert System for Interpretation of Geotechnical Characterization Data From Cone Penetrometers." PhD., Thesis, Carnegie-Mellon University, Pittsburgh.

Mullarkey, P.W. (1987). "Languages and Tools for Building Expert Systems," in Expert Systems for Civil Engineers, ASCE, New York, pp. 15-34.

Nebendahl, D. (1988). Expert Systems, Simen Aktiengesellschaft, Berlin.

Newman, M. (1976). Standard Cantilever Retaining Walls, Robert E. Krieger Publishing Company, Florida.

Newell, A. (1977). "Knowledge Representation Aspects of Production Systems." Proc., Fifth IJCAI, pp. 987-988.

Nii, P., (1986). "The Blackboard Model of Problem Solving." AI Magazine, pp. 38-53.

Nilson, A.H., and Winter, G. (1986). Design of Concrete Structures, 10th Edition, McGraw-Hill, New York.

Peck, R.B., Ireland, H.O., Teng, C.Y. (1948). A Study of Retaining Wall Failures, Proc. 2nd International Conference Vol. III, Rotterdam, pp. 296-299.

Peck, R.B., Hanson, W.E., Thornburn, T.H. (1974). Foundation Engineering, John Willy & Sons, New York.

Prerau, D.S. (1989). "Choosing An Expert System Domain." in Topics in Expert System Design, G., Guida and C., Tasso, eds., Elsevier New York, pp. 27-43.

Price, W.A., et al. (1980). User's Guide: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Flood Walls (TWDA), Instruction Reports K-80-6, K-80-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Rehnman, S.E., and Broms, B.B. (1972). "Lateral Pressures on Basement Wall: Results from Full Scale Tests." Proc. 5th European Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp. 189-197.

Rhomberg, E.J., and Street, W.M. (1981). "Optimal Design of Retaining Walls." Journal of Structural Division, ASCE, pp. 992-1002.

Rich, E. (1983). Artificial Intelligence, McGraw-Hill, New York.

Rychener, M.D. (1988). "Research in Expert Systems for Engineering Design." in Expert Systems for Engineering Design, Academic Press, Inc., Boston, pp. 1-33.

Rowe, P.W., and Peaker, K. (1965). "Passive Earth Pressure Measurements." Geotechnique, Vol. 15, No. 1, pp. 57-77.

Rowe, P.W. (1969). "Progressive Failure and Strength of a Soil Mass." Proc., 7th International Conference of Soil Mechanics and Foundation Engineering, Vol. 1, pp. 346-349.

Samuel, A.L. (1963). "Some Studies in Machine Learning Using the Game of Checkers." in Computers and Thought, E.A. Feigenbaum and J. Feldman, eds., McGraw-Hill, New York.

Sherif, M.A., Ishibashi, I., and Lee, C.D. (1982). "Earth Pressure Against Rigid Retaining Walls." Journal of Geotechnical Engineering Division, ASCE, Vol. 108, No,GT5, May, pp. 679-695.

Sherif, M.A., Fang, Y-S, and Sherif, R.I. (1984). "Ka and Ko Behind Rotating and Non-Yielding Walls." Journal of Geotechnical Engineering, ASCE, Jan., pp. 41-56.

Shields, D.H, and Tolunay, A.Z. (1973). "Passive Pressure Coefficients by Method of Slices." Journal of the Soil Mechanics and Foundation Division, Vol. 99, SM12, pp 1043--1051.

Shortliffe, E.H. (1976). Computer-Based Medical Consultation: MYCIN, American Elsevier, New York.

Stefik, M.J. (1979). "An Examination of a Frame-Structured Representation System." Proc., Sixth IJCAI, pp. 845-852.

Stiles, J.W., (1970). "Practical Aspects of Cantilever Retaining Wall Design." Highway Research Record No 302, Washington D.C., pp. 87-96.

Strom. R. (1991). Personal Communication.

Terzaghi, K. (1920). "Old Earth Pressure Theories and New Test Results." Engineering News Record, Vol. 85, No. 14, Sept., pp. 630-637.

Terzaghi, K. (1934). "Large Retaining Wall Tests." Engineering News Record, Vol. 112, Feb. 1 - Mar. 29.

Terzaghi, K. (1936). "A Fundamental Fallacy in Earth Pressure Computations." Journal of the Boston Society of Civil Engineers, Apr., pp. 71-80.

Terzaghi, K. (1940). "Earth Pressure of Sand on Walls." abstracted by Rutledge P.C., Proc. Purdue Conference on Soil Mechanics and its Applications, Sept., pp. 241-258.

Terzaghi, K., and Peck, R.B. (1967). Soil Mechanics in Engineering Practice, 2nd Edition, John Willy, New York.

Tschebatarioff, G.P. (1951). Soil Mechanics, Foundations, and Earth Structures, McGraw-Hill, New York.

Tschebatarioff, G.P. (1973). Soil Mechanics, Foundations, and Earth Structures, McGraw-Hill, New York.

U.S. Army (1989). Engineering and Design: Retaining and Flood Walls, EM 1110-2-2502, Department of the U.S. Army Corps of Engineers, Washington D.C. van Melle, W. (1979). "A Domain Independent Production-Rule System for Consultaion Programs." Proc., Sixth IJCAI, pp. 923-925.

Wang, C.H., and Salmon, C.G. (1985). Reinforced Concrete Design, 4th Edition, Happer and Row, New York.

Weiss, S.M. and Kulikowski, C.A. (1979). "EXPERT: A System for Developing Consultation Models." Proc., Sixth IJCAI, pp. 942-947.

Winston, J.L. (1977). Artificial Intelligence, Addison Wesley Publishing Company, Massachusetts.

Wright, W.V., Coyle, H.M., Bartoskewitz, R.E. (1975). "New Retaining Wall Design Criteria Based on Lateral Earth Pressure Measurements." Research Report No. 169-4F, Texas Transportation Institute, Texas A&M University.

Wu, T.H. (1966). Soil Mechanics, Allyn and Bacon, Boston.

Wu, T.H. (1975). "Retaining Walls." Chapter 12, Foundation Engineering Handbook by H.F. Winterkorn and H-Y Fang, Van Nostrand Reinhold, New York.

Wu, T.H. (1976). Soil Mechanics, Allyn and Bacon, Boston.

APPENDICES

APPENDIX A

QUESTIONNAIRE ON CANTILEVER WALL DESIGN

APPENDIX A

QUESTIONNAIRE ON CANTILEVER WALL DESIGN

The purpose of this questionnaire is to elicit knowledge from experts familiar with the design and construction of retaining structures. The knowledge thus elicited will be used to write heuristics (rules and "rules of thumb") for an expert system being developed for the preliminary design of cantilever retaining walls.

PART 1

Wall Proportions and External Stability

Q1. Cantilever retaining walls are most appropriate for wall heights of _______ to _______ feet.

Q2. The design of cantilever retaining walls is a trial and error process. What initial trial dimensions should be assumed to minimize the number of trials?

a. Stem bottom thickness as % of wall height ___
b. Base thickness as % of wall height ___
c. Base width as % of wall height ___
d. Heel length as % of base width ___

Q3. What should be the minimum top stem thickness for various wall heights?

a. less than 10 feet _____ in
b. 10 to 20 feet _____ in
c. over 20 feet _____ in

Q4. Cohesionless backfills are generally recommended for retaining walls. The angle of internal friction (Φ) of cohesionless soils may vary between about 28 and 45 degrees depending on soil type and degree of compaction. What friction angles do you recommend for the soils given below? The soils are classified according to Unified Soil Classification System.

Soil type		Angle to be used in actual design (degrees)	Expected angle (degrees)
1. Well compacted			
	a. GW, SW	_______	_______
	b. GP, SP	_______	_______
	c. GM, SM	_______	_______
	d. GC, SC	_______	_______
2. Loose			
	a. GW, SW	_______	_______
	b. GP, SP	_______	_______
	c. GM, SM	_______	_______
	d. GC, SC	_______	_______

Q5. What unit weights do you recommend for the following soils if used as wall backfill?

Soil type		Unit weight pcf
1. Well compacted		
	a. GW, SW	_______
	b. GP, SP	_______
	c. GM, SM	_______
	d. GC, SC	_______
2. Loose		
	a. GW, SW	_______
	b. GP, SP	_______
	c. GM, SM	_______
	d. GC, SC	_______

Q6. Which theory do you prefer for computing lateral earth pressure behind cantilever retaining walls?

a. Coulomb's theory.
b. Rankine's theory.
c. Either theory can be used.

Q7. Coulomb's theory assumes a planar wall back face for predicting lateral earth pressure behind retaining structures but cantilever retaining walls have vertical back face (i.e., vertical stem and horizontal heel). How does this assumption affect earth pressure predictions behind cantilever retaining walls?

Q8. Rankine's theory neglects wall friction for earth pressure computations but experimental and full-scale tests show that friction does develop between wall back face and the backfill. How does the neglect of wall friction affect wall design? (e.g., effect on wall dimensions and overall cost)

Q9. Both Coulomb and Rankine,s theories can be used for predicting earth pressure behind a wall with dry or fully saturated backfills. How is the earth pressure effected when these theories are used for earth pressure prediction behind a wall where water table is present.

Q10. What value of wall friction angle (δ) do you consider most appropriate when Coulomb's theory is used for earth pressure prediction with sloping backfills?

a. $\delta=0$
b. $\delta=\beta$
c. $\delta=\Phi$
d. $\delta=(\beta+\Phi)/2$
e. $\delta=2/3\ \Phi$
f. other

Q11. Should the same wall friction angle (δ) be used for computing earth pressure on stem and wall? In not, what different values do you recommend?

Q12. In earth pressure computations generally, a hydrostatic pressure distribution is assumed behind retaining walls and the total earth force is assumed to act at one third of wall height from wall base. Experimental and full-scale tests show that the resultant of forces may act higher than the one-third of wall height from base and pressure distribution depend on amount and type of wall movements. In your opinion what pressure distribution should be assumed behind the wall and where would the point of application of total force to be considered to act?

Q13. Compaction may induce higher pressures than active behind the wall. How can the compaction effects can be incorporated in the design.

a. By considering point of application of resultant of forces to act at 0.4 to 0.5H instead of 0.33H.
b. By limiting the weight of roller so that compaction does not induce residual pressures.
c. By neglecting compaction effects.
d. Any other method

Q14. Some designers and agencies recommend to assume at-rest conditions behind cantilever retaining walls for computing lateral earth pressure irrespective of walls rigidity. Is it appropriate in your opinion? Why and why not?

Q15. Many designers neglect passive resistance on toe side of the wall for stability checks. Which of the following is appropriate?

a. Neglect the passive resistance completely.
b. Consider passive resistance at most equal to half the value of passive earth pressure.
c. Consider passive resistance equal to the passive earth pressure and use higher safety factors against wall overturning and sliding.

Q16. What minimum safety factors do you recommend to ensure wall safety against overturning, sliding and bearing capacity failures?

a. Overturning failures __________
b. Sliding failures __________
c. Bearing capacity failures __________

Q17. Which of the following criterion is more appropriate to ensure stability against wall overturning?

a. Incorporate adequate safety in the design.
b. Ensure resultant of forces remain within middle third of wall base.
c. Either "a" or "b" is appropriate
d. Others.

Q18. What possible measures can improve the stability of a cantilever retaining wall if it fails in overturning during stability checks.

Q19. How wall stability against sliding failures can be improved?

Q20. If passive resistance in front of the wall is to be considered. Which of the equation given below is more appropriate for computing safety factor against sliding failures?

a. $F.S.(s) = (V\tan\Phi + cB + P_{RH}/P_{DH}$
b. $F.S.(s) = (V\tan\Phi + cB)/(P_{DH} - P_{RH})$
c. Others

where
V =total effective vertical force acting under the base

P_{RH}=horizontal passive resistance on toe side of the wall
P_{DH}= horizontal driving force on heel side of the wall
c =cohesion of foundation soil

Q21. Large wall movements are required for a cantilever wall to fail in sliding and active condition are expected to be induced in the backfill due to these movements. Therefore, some designers recommend that P_{DH} for sliding analysis should always be computed assuming active conditions behind the wall. What do you recommend?

Q22. When undrained shear strength parameters (c and Φ) of foundation soil are used, what reduction factor should be used with cohesion term "c" as given in sliding stability equation of Q20?

Q23. For sliding stability analysis, many designer believe that the wet concrete adhere sufficiently to the foundation soil and friction angle between wall base and foundation soil as same as internal friction angle of foundation soil. Is it appropriate in your opinion?

Q24. The presence of water on heel on toe side of the wall induces uplift pressure beneath the wall. How does uplift pressure affect wall stability against sliding and bearing capacity failures and how its effects can be incorporated in the design?

Q25. How can the stability of a cantilever retaining wall be improved if the wall fails in bearing capacity during stability checks?

Q26. If the eccentricity exceeds limits in the design process (i.e., resultant of forces acts out of middle third of wall base). What measures can help to bring eccentricity within limits in cases given below?

a. When the resultant acts out of middle third on toe side of the wall from middle of base.

b. When the resultant acts out of middle third on heel side of the wall from base mid point.

Q27. Do you recommend the use of base key in routine design of cantilever retaining walls? or should the base key be only used to avoid base length becoming excessively long because of sliding stability requirement in week foundation soils.

Q28. What can be the maximum base length (B) in term of wall

height (H)?
a. B = H
b. B = 1.5H
c. B = 2H
d. No limits

Q29. For computing safety factor against bearing capacity failures, which of the following is more appropriate?

a. Use average soil pressure under the base
b. Use maximum soil pressure under the base
(If (a), neglect the next question)

Q30. Non-uniform pressure distribution under the base is caused by eccentric loading on the wall. The effect of eccentricity is already incorporated in the design by reducing the base length in bearing capacity equations recommended by Meyerhof and Hansen. If this approach is used, will not, the use of maximum soil pressure under the base for computing safety factor against bearing capacity make the design conservative?

PART 2

Structural Design of Cantilever Retaining Wall

Q31. Are the provision of ACI code 318-83 adequate for the design of cantilever retaining wall? If not, what modification do you recommend?

Q32. The following approaches are commonly used for heel design:

Approach 1:- Neglect soil pressure under the heel and apply load factors to dead loads and live load over the heel.

Approach 2:- Consider soil pressure under the heel and subtract it from the loads over the heel before applying the load factors.

Which approach do you consider more appropriate

1. Approach 1
2. Approach 2

(If the answer is 2 , go to Q34)

Q33. The application of load factors is not apparent from the ACI Code. What load factor do you recommend for the structural design of the wall parts when base soil pressure is neglected for heel design.

Stem
- Under active conditions ______
- Under at-rest condition ______

Heel
- Dead load over heel ______
- Live load over heel ______

Toe
- Dead load over toe ______
- Soil pressure under toe ______

Q34. What load factor do you recommend for the structural design of the wall parts when base soil pressure is considered for heel design

Stem
- Under active conditions ______
- Under at-rest conditions ______

Heel
- Net load on heel ______

Toe
- Net load on toe ______

Q35. Where the critical sections be taken for the flexural and shear design of stem, heel and toe?

Moment
- Stem ______
- Heel ______
- Toe ______

Shear
- Stem ______
- Heel ______
- Toe ______

Q36. What can be the approximate difference in cost per foot of wall under active and at-rest conditions?

APPENDIX B

EXAMPLE RUN

APPENDIX B

EXAMPLE RUN

B1. TWALL Solution of Example 1, Appendix N, The U.S. Army Corps of Engineers (EM 1110-2-2502 1989)

This section contains a transcript of a sample run of TWALL and demonstrates the interaction between TWALL and the program user. The user responses are hatched for clarity.

....

W E L C O M E   T O   T W A L L

AN EXPERT SYSTEM FOR THE
PRELIMINARY DESIGN OF CANTILEVER
RETAINING WALLS

BY

NASRULLAH ABEER AND DR. THOMAS F. WOLFF
MICHIGAN STATE UNIVERSITY

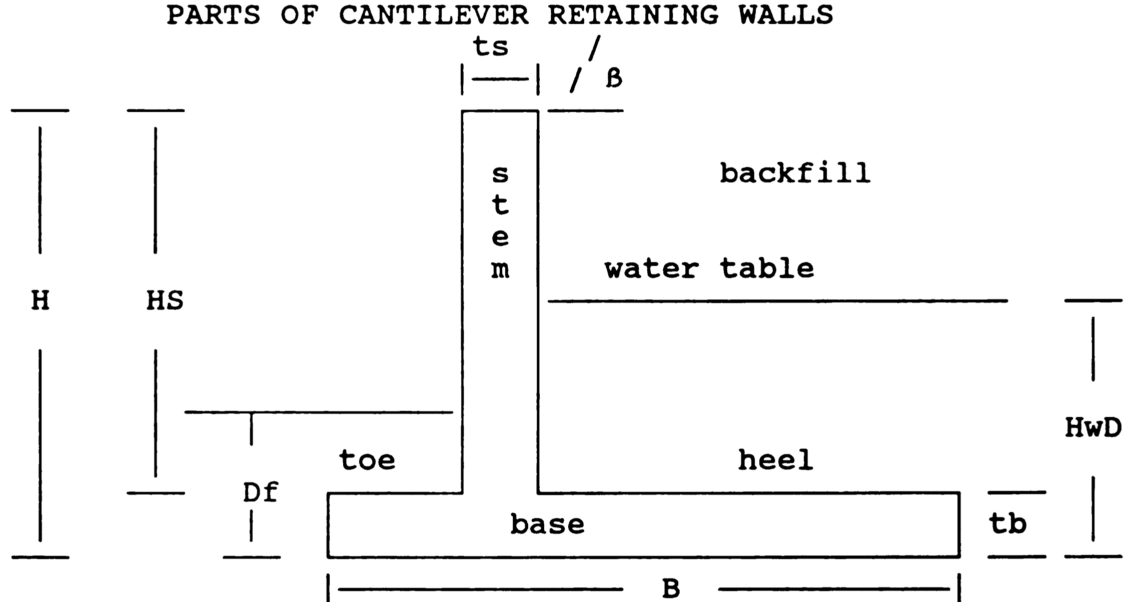
Press <F1> function key or <Page down> to see next page

I N T R O D U C T I O N

TWALL is an expert system for the preliminary design of cantilever retaining walls. In TWALL, you have an option to design the wall for external stability only or for both external stability and internal stability. For the present design, the system will first check the suitability of the wall for a given application by asking you few questions. Then you will also be asked required design parameters during consultation session. For external stability, the system will check wall stability against overturning, sliding, and bearing capacity failures. For both external and internal stability, system will first ensure external stability and then will calculate required steel for stem heel and toe and perform cost analysis. The wall design has implemented in Foot-Pound System of units. The function keys at the bottom of screen are available for use when illuminated.

Press <Enter> to continue	F1-Pg down	F9 - Help

PARTS OF CANTILEVER RETAINING WALLS



Press <Enter> to continue or <F1> to see notations

Using keyboard arrows, place the arrow ===> beside your area of interest and press <Enter> to make selection. After making your selection, press <F4> to continue. Press <F5> to know more about external and internal stability

External Stability

Internal Stability

Wall height (H) ?

Permissible range: H = 6 to 30 ft

25

Is granular material available for use as backfill?

TRUE FALSE

Foundation soil is not highly compressible

TRUE FALSE

Have technical know-how

TRUE FALSE

Have required plant and equipment for wall construction

TRUE FALSE

A cantilever retaining wall is not suitable for present application according to criteria laid in this knowledge base. However, if <TRUE> you still have the option to continue with the design.

Use horizontal arrow keys to move cursor between <TRUE> and <FALSE> and Press <Enter> to continue

TRUE FALSE

Internal friction angle of backfill soil (Φ1) ?

Recommended values: Φ1 = 30 to 36 deg
Permissible values: Φ1 = 20 to 45 deg

35

Internal friction angle of foundation soil (Φ2) ?

Recommended values:

Cohesionless soils $\Phi 2$ = 30 to 36 deg
Cohesive soils $\Phi 2$ = 0 to 20 deg

Permissible values: $\Phi 2$ = 0 to 45 deg

40

Cohesion of foundation soil (c2) ?

Recommended values:

when $\Phi 2>20$ c2 = 0 to 1500 psf
when $\Phi 2<20$ c2 = 500 to 4000 psf

Permissible values: c2 = 0 to 4000 psf

0

Unit weight of backfill soil ($\Gamma 1$)?

Recommended values: $\Gamma 1$ = 100 to 125 pcf
Permissible values: $\Gamma 1$ = 80 to 150 pcf

Note:- The required unit weight is moist. In case of water presence, the system will increase this weight according to the heuristics incorporated in the system to make it saturated.

120

Unit weight of foundation soil ($\Gamma 2$) ?

Recommended values: $\Gamma 2$ = 100 to 130 pcf
Permissible values: $\Gamma 2$ = 80 to 150 pcf

135

Note: The soil weight being asked is moist.

Backfill slope angle (ß)?

Permissible values: 0 <ß< 35.0 deg

18.43

Do you want to enter wall friction angle of your choice?
Enter "TRUE"

If "FALSE" the system will assume default wall friction angle i.e., $\delta=(\beta+\Phi)/2=26.7$

Press <F5> function key to know more about wall friction.

TRUE FALSE

Wall friction angle (δ) ?

Permissible values: $10.0 < \delta < 35.0$ deg

18.43

Uniform surcharge (qo)?

Permissible values: qo = 0 to 3000 psf

Press <F5> function key to know about surcharge

0

Embedment depth (Df) ?

Recommended values: 2 <Df< 6

Press <F5> function key to know more about embedment depth

E M B E D M E N T D E P T H

A vertical distance to which the base in front of a retaining wall is laid below ground surface is called embedment depth.The base should be placed below the depth of frost action, zone of seasonal variation and depth of scour. The embedment depth may not exceed half the base length so that the assumption of shallow foundation in not violated.

Press <Enter> to continue

Embedment depth (Df) ?

Recommended values: 2 <Df< 6

Press <F5> function key to know more about embedment depth

3

Is the water table at or above the bottom of wall base? If "FALSE", the system will assume water table below the base.

TRUE FALSE

Depth of water table below wall base, (dw)?

Permissible range: dw>=0

(Water has no effect if water table is below 26.8 ft. from wall base)

30

E A R T H P R E S S U R E

Do you assume active conditions behind the wall for earth pressure computations? If "TRUE", the system will assume Coulomb's active conditions. If <FALSE> the wall will be design for at-rest conditions. Coulomb and Rankine's theories yields the same results for $\delta=\beta$.

TRUE FALSE

O V E R T U R N I N G S T A B I L I T Y

Safety factor for wall stability against overturning?

Enter <TRUE> to use default value (i.e., F.S.otReq=2).
Enter <FALSE>, to change the default value.

TRUE FALSE

Safety factor against overturning?

Recommended values: 1.50 <F.S.otReq< 2.50
Permissible values: 1.25 <F.S.otReq< 3.50

2.25

S L I D I N G S T A B I L I T Y

Safety factor for wall stability against sliding failures?

Enter <TRUE> to use default value (F.S.sReq=1.5).
Enter <FALSE>, to change the default value.

TRUE FALSE

B E A R I N G   C A P A C I T Y

Safety factor to ensure adequate bearing capacity of the foundation soil?

Enter <TRUE> to use default value (F.S.bReq=3).
Enter <FALSE>, to change the default value.

TRUE   FALSE

W A L L   S T A B I L I T Y

After obtaining the required parameters, now we will evaluate the stability of the wall assuming trial dimensions. The wall is considered safe against overturning, sliding and bearing capacity failures if calculated safety factors are larger than the safety factors given below:

Safety factor against wall overturning   >=2.25
Safety factor against sliding failures   >=1.50
Safety factor against bearing failures   >=3.00

Please press <Enter> to continue

Base width (B) ?

Recommended width: 12.50 <B< 15.00 ft
Permissible width: 10.00 <B< 25.00 ft

9

O U T   O F   R A N G E

The number you enter is out of range for this knowledge base. Please see the range and enter it again.

Please press <Enter> to continue

Base width (B) ?

Recommended width: 12.50 <B< 15.00 ft
Permissible width: 10.00 <B< 25.00 ft

15

Heel length ?

Recommended length: 8.55 <heel< 9.00 ft
Permissible length: 7.50 <heel< 9.75 ft

8

Thickness of base (tb) ?

Recommended base thickness:

When H<10	**tb = 1**	**ft**
When 10<H<20	**tb = 1 to 2**	**ft**
When 20<H<30	**tb = 2 to 3**	**ft**

Permissible base thickness: 1.79 <tb< 4.17 ft

3.00

T O P   S T E M   T H I C K N E S S

Default top stem thickness tst = 1 ft
If <TRUE>, the system will assume default value.
Else, enter <FALSE>, to change the default value.

TRUE   **FALSE**

Top stem thickness?

Permissible values: 1 <tst< 2 ft
Recommended values:

ts = 0.75 ft	when H<10 ft
ts = 1.00 ft	when 10<H<20 ft
ts = 1.50 ft	when H>20 ft

1.5

O V E R T U R N I N G   F A I L U R E

The wall design is unsafe as the safety factor against overturning moments 2.04 is less than 2.25. The system will increase 20.2 % heel length and 25.2 % base length, as you press <Enter> and it will recalculate the safety factor against overturning. However, you have an option to change these dimensions using "WHY" and "FACTS MENU".

B = 15.00 ft
Heel = 8.00 ft
toe = 4.51 ft

Please press <Enter> to continue

B A S E   K E Y

Do you want to design cantilever wall with base key? If "FALSE", the system will design the wall without base key.

TRUE   **FALSE**

Yield strength of steel, fy?

Permissible range: 30<fy<80 Ksi

60

Allowable compressive concrete strength, f'c?

Permissible range: 3 <f'c< 5 Ksi

3

B A S E   S O I L   P R E S S U R E

If you want to consider base soil pressure for the structural design of heel. Enter <TRUE>. Else enter <FALSE>.

Press <F5) function key to know more about soil pressure

TRUE   FALSE

O V E R L O A D   F A C T O R S

Default load factors for the structural design

a. When base soil pressure is not neglected.
   Load factor for stem, heel, and toe = 1.7

b. When base soil pressure is neglected.
   Load factor for stem and toe = 1.7
   Load factor for heel = 1.4

If <TRUE>, the system will use the default values.
Else enter <FALSE> to change the default values.

TRUE   FALSE

Overload factor?

Recommended range: 1.7 <LF< 1.9

1.9

The trial design is safe against overturning, sliding and bearing capacity failures. Now we will compute shears, moments and area of required steel for stem, heel and toe to ensure internal stability of the wall.

C O S T   A N A L Y S I S

The default materials costs based on Means Construction Data 1990, used in this knowledge base are:

Excavation	$	8.0	/c.y.
Granular Backfill	$	11.0	/c.y.
Inplace Concrete	$	240.0	/c.y.

If <TRUE>, the system will assume the default values. If <FALSE>, Press <Enter> to change the default values.

TRUE   FALSE

D E S I G N   S U M M A R Y

Safety factor against wall overturning = 2.83
Safety factor against sliding failures = 1.68
Safety factor against bearing failures = 8.03

Wall height	ft	= 25.0
Wall height above ground surface	ft	= 22.00
Stem height	ft	= 22.00
Top stem thickness	ft	= 1.50
Bottom stem thickness	ft	= 2.49
Base width	ft	= 18.78
Heel length	ft	= 9.62
Toe length	ft	= 6.67
Base thickness	ft	= 3.00
Stem steel	sq-in/ft	= 1.96
Heel steel	sq-in/ft	= 1.88
Toe steel	sq-in/ft	= 1.30
Cost	$/ft	= 1100.82

SUMMARY OF COMPUTATIONS

1. INPUT DATA

Backfill soil friction angle	$\Phi 1$	= 35.00	deg
Foundation soil friction angle	$\Phi 2$	= 40.00	deg
Foundation soil cohesion	c2	= 0.00	psf
Unit weight of backfill soil	$\Gamma 1$	= 120.00	pcf
Unit weight of foundation soil	$\Gamma 2$	= 135.00	pcf
Backfill slope angle	β	= 18.43	deg
Wall friction angle	δ	= 18.43	deg
Uniform surcharge	qo	= 0.00	psf
Embedment depth	Df	= 3.00	ft

2. EXTERNAL STABILITY

Coefficient of earth pressure	K =0.561
Lateral earth force on stem	P =16298 Ibs
Horizontal force on stem	Ph =15463 Ibs
Lateral earth force on wall	PsD=26788 Ibs
Total net horizontal force	PH=25414 Ibs
Total downward vertical force	V=50744 Ibs
Effective vertical force	N'=50744 Ibs
Safety factor against overturning	= 2.83
Safety factor against wall sliding	= 1.68
Eccentricity	e=0.78 ft
Safety factor against bearing capacity failures	Qult/N' = 8.03

3. STRUCTURAL DESIGN

PRESSURES SHEARS AND MOMENTS

a. Stem

Distance from top of stem	Pressures psf	Shears Ibs	Moments Ib-ft
0.0	0	0	0
5.5	704	1836	3366
11.0	1408	7345	26931
16.5	2399	18779	103286
22.0	2815	29379	215446

b. Heel

Distance from free end of heel	Pressures psf	Shears Ibs	Moments Ib-ft
0.0	2717	0	0
2.4	2215	22020	47658
4.8	1712	26740	68956
7.2	1209	30252	184574
9.9	707	32555	258884

c. Toe

Distance	Pressures	Shears	Moments

from free end of toe	psf	Ibs	Ib-ft
0.0	5565	0	0
1.7	5336	9094	7640
3.3	5108	17807	30134
5.0	4879	26138	66847
6.7	4650	34088	117143

STEEL REINFORCEMENT

a. Stem

Steel at stem top	sq-in/ft	= 0.58
Steel at stem middle	sq-in/ft	= 0.82
Steel at stem bottom	sq-in/ft	= 1.96

b. Heel

Steel at heel free end	sq-in/ft	= 1.30
Steel at mid heel	sq-in/ft	= 1.30
Steel at heel near end	sq-in/ft	= 1.88

c. Toe

Steel at toe free end	sq-in/ft	= 1.30
Steel at mid toe	sq-in/ft	= 1.30
Steel at toe near end	sq-in/ft	= 1.30

4. COST ANALYSIS

Backfill cost	= 193.02	$/ft of wall
Concrete cost	= 891.10	$/ft of wall
Excavation cost	= 16.70	$/ft of wall
Total	=1100.82	$/ft of wall

B2. TWALL Solution of Example 12.4 (Bowles 1982)

DESIGN SUMMARY

Safety factor against wall overturning = 2.60
Safety factor against sliding failures = 2.02

Safety factor against bearing failures = 5.17

Wall height	**ft**	**= 28.40**
Wall height above ground surface	**ft**	**= 23.40**
Stem height	**ft**	**= 25.98**
Top stem thickness	**ft**	**= 1.25**
Bottom stem thickness	**ft**	**= 1.89**
Base width	**ft**	**= 14.64**
Heel length	**ft**	**= 9.00**
Toe length	**ft**	**= 3.74**
Base thickness	**ft**	**= 2.42**
Stem steel	**sq-in/ft**	**= 2.30**
Heel steel	**sq-in/ft**	**= 1.62**
Toe steel	**sq-in/ft**	**= 1.02**
Cost	**$/ft**	**= 905.05**

SUMMARY OF COMPUTATIONS

1. INPUT DATA

Backfill soil friction angle	Φ1	= 34.00	deg
Foundation soil friction angle	Φ2	= 32.00	deg
Foundation soil cohesion	c2	= 400.00	psf
Unit weight of backfill soil	Γ1	= 115.00	pcf
Unit weight of foundation soil	Γ2	= 112.00	pcf
Backfill slope angle	ß	= 10.00	deg
Wall friction angle	δ	= 10.00	deg
Uniform surcharge	qo	= 0.00	psf
Embedment depth	Df	= 5.00	ft

2. EXTERNAL STABILITY

Coefficient of earth pressure	K =0.294
Lateral earth force on stem	P =11425 Ibs
Horizontal force on stem	Ph =11251 Ibs
Lateral earth force on wall	PsD=15220 Ibs
Total net horizontal force	PH=14889 Ibs
Total downward vertical force	V=41794 Ibs
Effective vertical force	N'=41794 Ibs
Safety factor against overturning	= 2.60
Safety factor against wall sliding	= 2.02
Eccentricity	e=1.59 ft

Safety factor against bearing capacity failures
Qult/N' = 5.17

3. STRUCTURAL DESIGN

PRESSURES SHEARS AND MOMENTS

a. Stem

Distance from top of stem	Pressures psf	Shears Ibs	Moments Ib-ft
0.0	0	0	0
6.5	396	1266	2740
13.0	792	5063	21923
19.5	1298	12453	80882
26.0	1583	20252	175383

b. Heel

Distance from free end of heel	Pressures psf	Shears Ibs	Moments Ib-ft
0.0	4558	0	0
2.3	3449	13765	22313
4.5	2341	20280	51990
6.8	1233	24301	118704
9.3	125	25828	175049

c. Toe

Distance from free end of toe	Pressures psf	Shears Ibs	Moments Ib-ft
0.0	7308	0	0
0.9	6880	6640	3139
1.9	6453	12880	12305
2.8	6026	18720	27126
3.7	5598	24160	47225

STEEL REINFORCEMENT

a. Stem

Steel at stem top	sq-in/ft	= 0.46
Steel at stem middle	sq-in/ft	= 0.61
Steel at stem bottom	sq-in/ft	= 2.30

b. Heel

Steel at heel free end	sq-in/ft	= 1.02
Steel at mid heel	sq-in/ft	= 1.02
Steel at heel near end	sq-in/ft	= 1.62

c. Toe

Steel at toe free end	sq-in/ft	= 1.02
Steel at mid toe	sq-in/ft	= 1.02
Steel at toe near end	sq-in/ft	= 1.02

4. COST ANALYSIS

Backfill cost	= 205.42	$/ft of wall
Concrete cost	= 677.95	$/ft of wall
Excavation cost	= 21.69	$/ft of wall
Total	= 905.09	$/ft of wall

APPENDIX C

TWALL: SAMPLE RULES AND PROCEDURES

APPENDIX C

TWALL: SAMPLE RULES AND PROCEDURES

C1. Sample Rules

```
! Rules that give an option to the program user to
! design the wall for external or internal stability
! and specifies the facts required to be proved before
! the system reaches a conclusion of safe design.

RULE  evaluate external stability
IF    required IS external stability
THEN  Evaluate for external stability
AND   stability:="external stability"

RULE  evaluate internal stability
IF    required IS internal stability
THEN  Evaluate for internal stability
AND   stability:="internal stability"

RULE  external stability
IF    stability:="external stability"
AND   cantilever wall is suitable for present:
      application
AND   know parameters
AND   know trial wall dimensions
AND   wall is externally stable
AND   DISPLAY design summary1
AND   know activate external program
THEN  External wall design is safe
ELSE  DISPLAY design unsafe

RULE  internal stability
IF    stability:="internal stability"
AND   cantilever wall is suitable for present:
      application
AND   know parameters
AND   know trial wall dimensions
AND   wall is externally stable
AND   wall is internally stable
AND   know cost analysis
AND   DISPLAY design summary2
```

```
AND   know activate external program
THEN  cantilever wall design is safe
ELSE  DISPLAY design unsafe


! Rules to check the suitability of a cantilever wall
! for a given application.

RULE  wall suitability
IF    H<=30
AND   H>=6
AND   Granular backfill
AND   Foundation soil is not highly compressible
AND   Have technical know_how
AND   Have required plant and equipment for:
      wall construction
THEN  wall suitability1

RULE  wall suitability
IF    wall suitability1
OR    user preference
THEN  cantilever wall is suitable for present:
      application
ELSE  cantilever wall is unsuitable
AND   DISPLAY wall unsuitable
AND   FORGET ALL
AND   CYCLE


! Rules to query the user for required overturning
! safety factor or to assign default value

RULE  default safety factor
IF    F.S.ot preference
THEN  know required F.S.ot
AND   F.S.otReq:=2

RULE  optional safety factor
IF    NOT F.S.ot preference
AND   F.S.otReq>=1.25
AND   F.S.otReq<=3.5
THEN  know required F.S.ot


! Rule to query the user for trial base width. "Ba"
! and "Bb" are ranges of recommended base widths and
! "Ba1" and "Bb1" are maximum base widths which are
! displayed to the user when queried.

RULE  base width
IF    Ba:=0.4*H
AND   Bb:=H
AND   Ba1:=0.5*H
```

```
AND    Bb1:=0.8*H
AND    B>=0.4*H
AND    B<=H
THEN   know B
ELSE   DISPLAY out of range
AND    FORGET B
AND    FORGET Ba
AND    FORGET Bb
AND    FORGET Ba1
AND    FORGET Bb1
AND    CYCLE


! Rules to determine toe length.

RULE   toe length
IF     δ=0
AND    toe:=B-(heel+tsb)
AND    toeMin:=0.24*B
AND    toe>=toeMin
THEN   know toe

RULE   toe length
IF     δ>0
AND    δ<=0.5*Φ1
AND    toe:=B-(heel+tsb)
AND    toeMin:=0.26*B
AND    toe>=toeMin
THEN   know toe

RULE   toe length
IF     δ>0.5*Φ1
AND    toe:=B-(heel+tsb)
AND    toeMin:=0.30*B
AND    toe>=toeMin
THEN   know toe

RULE   toe length
IF     toe<toeMin
THEN   know toe
AND    toe:=toeMin
AND    B:=toe+tsb+heel


! Rule that shows the facts to be established for
! the external stability of the wall.

RULE   external stability
IF     know wall forces
AND    wall is safe against overturning forces
AND    wall is safe against sliding forces
AND    wall is safe against bearing capacity failure
THEN   wall is externally stable
```

```
! Rule to calculate lateral earth force on the wall

RULE  lateral force due to soil PsD
IF    σ1  :=K*qo
AND   σ2  :=K*Γ1*(heel*TAN(ß*0.0174533)+H-HwD)
AND   σ3  :=σ2+K*(1.05*Γ1-62.4)*HwD
AND   PD1 :=σ1*(H+heel*TAN(ß*0.0174533))
AND   PD2 :=0.5*σ2*(heel*TAN(ß*0.01745)+H-HwD)
AND   PD3 :=σ2*HwD
AND   PD4 :=0.5*(σ3-σ2)*HwD
AND   PsD  :=PD1+PD2+PD3+PD4
THEN  know PsD


! Rules to determine factor of safety against
! wall overturning. If the trial wall design fails, the
! rule increases base and heel length in each cycle and
! recalculate safety factor. This iterative process
! continues until the wall is safe against overturning

RULE  safety against overturning
IF    know Mo
AND   know Mr
AND   F.S.otAval:=Mr/Mo
AND   F.S.otAval >=F.S.otReq
THEN  wall is safe against overturning forces

RULE  safety against overturning
IF    F.S.otAval <F.S.otReq
AND   Br:=100*(F.S.otReq-F.S.otAval)/:
      F.S.otAval+15
AND   heelr:=100*(F.S.otReq-F.S.otAval)/:
      F.S.otAval+10

!  where "Br" and "heelr" are recommended increase in
!  base and heel lengths which are displayed during
!  iterative design process for user information.
!
AND   DISPLAY overturning failure
AND   FORGET cantilever wall design is safe
AND   FORGET know trial wall dimensions
AND   FORGET know actual stem thickness
AND   FORGET know middle stem thickness
AND   FORGET know bottom stem thickness
AND   FORGET know toe
AND   FORGET wall is externally stable
AND   FORGET wall is safe against overturning:
      forces
AND   FORGET know wall forces
AND   FORGET know P
AND   FORGET know Phstem
AND   FORGET know PsD
AND   FORGET know PsDH
```

```
AND   FORGET know PsDV
AND   FORGET know PH
AND   FORGET know V1
AND   FORGET know V2
AND   FORGET know V3
AND   FORGET know V4
AND   FORGET know V5
AND   FORGET know V
AND   FORGET know u
AND   FORGET know N
AND   FORGET know Y
AND   FORGET know Mo
AND   FORGET know Mr1
AND   FORGET know Mr2
AND   FORGET know Mr3
AND   FORGET know Mr4
AND   FORGET know Mr5
AND   FORGET know Mr
AND   B:=1.15*B+B*((F.S.otReq-F.S.otAval)/:
      F.S.otAval))
AND   heel:=1.10*heel+heel*((F.S.otReq-F.S.otAval):
      /F.S.otAval))
AND   CYCLE
AND   F.S.otAval:=Mr/Mo
AND   F.S.otAval >=F.S.otReq
THEN  wall is safe against overturning forces


! Rule that shows the facts for stem design

RULE stem design
IF   know earth pressures on stem
AND  know earth forces on stem
AND  know shear on stem
AND  know moments on stem
AND  know stem reinforcement
THEN know stem is safe against shear and bending

RULE earth pressure at 0.25Hs from top
IF   HwD>0.75*Hs+tb
AND  HwR>0.75*Hs+tb
AND  p2a:=qo*K*LF
AND  p2b:=K*Γ1*(H-HwD)*LF
AND  p2c:=K*(1.05*Γ1-62.4)*(0.25*Hs-(H-HwD))*LF
AND  p2d:=62.4*(0.25*Hs-(H-HwD))*LF  ! WT on heel side
AND  p2e:=62.4*(0.25*Hs-(H-HwR))*LF  ! WT on toe side
AND  p2s :=p2a+p2b+p2c+p2d-p2e
THEN know p2s

RULE earth force at 0.25Hs from top
IF   HwD<=0.75*H+tb
AND  HwR<=0.75*H+tb
AND  Ps2a:=p2a*(Hs/4)
```

```
AND   Ps2b:=0.5*p2b*(Hs/4)
AND   Ps2:=Ps2a+Ps2b
AND   Y2:=(Ps2a*(Hs/8)+Ps2b*(Hs/12))/Ps2
THEN know Ps2

RULE shear on stem
IF    δ=0            ! wall friction angle
AND   Vs1:=Ps1       ! shear at stem top
AND   Vs2:=Ps2       ! shear at 0.25Hs from top
AND   Vs3:=Ps3       ! shear at stem middle
AND   Vs4:=Ps4       ! shear at 0.75Hs from top
AND   Vs5:=Ps5       ! shear at stem bottom
THEN know shear on stem

RULE  moments on stem
IF    Ms1:=0             ! moment at stem top
AND   Ms2:=Vs2*Y2        ! moment at 0.25Hs from stem top
AND   Ms3:=Vs3*Y3        ! moment at stem middle
AND   Ms4:=Vs4*Y4        ! moment at 0.75Hs from top
AND   Ms5:=Vs5*Y5        ! moment at stem bottom
THEN  know moments on stem

RULE  stem bottom reinforcement
IF    Know stem bottom max and min steel
AND   Know possible stem bottom steel
AND   Know required stem bottom steel
AND   know stem bottom steel within limits
THEN  know stem bottom reinforcement

! Rule to calculate cost per foot of wall

RULE  wall cost/ft
IF    Cexca:=CostExca*Vexca/27  !excavation cost/ft
AND   Cfill:=CostFill*Vfill/27    !backfill cost/ft
AND   Cconc:=CostConc*Vconc/27    !concretecost/ft
AND   cost:=Cfill+Cconc+Cexca
THEN  know total cost


! Rule to activate external graphics program

RULE  activate
ACTIVATE GTWALL.EXE
DISK  GDATA.PRL
SEND  H
SEND  Hs
SEND  tst
SEND  tsb
SEND  B
SEND  tb
SEND  heel
SEND  toe
THEN  know activate external program
```

C2. Sample Procedures

```
C************************ GTWALL ************************
C   Program GTWALL receive data from KBES TWALL through
C   disk file and draws final design sketch of cantilever
C   retaining wall. The program has been implemented in
C   Microsoft FORTRAN.
C*******************************************************

        INCLUDE  'FGRAPH.FI'
      COMMON /GRAPH/H,HS,TST,TSB,B,TB,HEEL,TOE
      OPEN(3,FILE='GDATA.PRL',STATUS='UNKNOWN')
      READ(3,*) NuVar
      READ(3,1) H    READ(3,1) HS
      READ(3,1) TST
      READ(3,1) TSB
      READ(3,1) B
      READ(3,1) TB
      READ(3,1) HEEL
      READ(3,1) TOE
 1    FORMAT(1X,E13.7)
      IF (B.GT.H) THEN
           XYMAX = B
      ELSE
        XYMAX = H
      ENDIF
         CALL graphicsmode(ASPECT, SCR)
      XMIN = -xymax/2.3
      XMAX = (XYMAX+xymax/2.30)*ASPECT/SCRt
      YMIN = -xymax/2.30
      YMAX = XYMAX+xymax/2.30
         CALL XYGRAPH(XMIN,XMAX,YMIN,YMAX)
        CALL endprogram()
      END
C
C*********************************************************
C     XYGRAPH - Subroutine to draw design sketch of the
C     cantilever retaining wall
C*********************************************************

       SUBROUTINE xygraph(XMIN,XMAX,YMIN,YMAX)
       INCLUDE  'FGRAPH.FD'
       COMMON /GRAPH/H,HS,TST,TSB,B,TB,HEEL,TOE
       INTEGER*2        dummy, newx, newy, locx, locy,i
       INTEGER*2  maxx, maxy
       EXTERNAL         newx, newy
       RECORD /xycoord/ xy
       RECORD /wxycoord/ xy1
       RECORD /rccoord/ curpos
       COMMON                maxx, maxy
       character*(10 ) fonnam/"t'courier'"/
       character*33 str
```

```
C
C     Calculate each position and display it on the screen.
C
C    Draw a rectangular border
C

      CALL moveto(1,1,xy)
      DUMMY = lineto(maxx-1,1)
      DUMMY = lineto(maxx-1,maxy-1)
      DUMMY = lineto(1,maxy-1)
      DUMMY = lineto(1,1)
      CALL moveto(2,2,xy)
      DUMMY = lineto(maxx-2,2)
      DUMMY = lineto(maxx-2,maxy-2)
      DUMMY = lineto(2,maxy-2)
      DUMMY = lineto(2,2)
C
      DUMMY = SETWINDOW(.FALSE.,XMIN,YMIN,XMAX,YMAX)
      CALL SETVIEWORG(50,0,xy)
C
      XC = 0.0
      YC =
      CALL moveto_w(XC,YC,xy1)
C
      YC = H - TB
      DUMMY = lineto_w(XC,YC)
C
      XC =  TOE
      DUMMY = lineto_w(XC,YC)
C
      XC = TOE + TSB - TST
      YC = 0.0
      DUMMY = lineto_w(XC,YC)
C
      XC = TOE + TSB
      DUMMY = lineto_w(XC,YC)
C
      YC = H - TB
      DUMMY = lineto_w(XC,YC)
C
      XC =  B
      DUMMY = lineto_w(XC,YC)
C
      YC = H
      DUMMY = lineto_w(XC,YC)
C
      XC = 0.0
      DUMMY = lineto_w(XC,YC)
C
     CALL VARROW(0.0,H,-B/5.0,1)
     i = registerfonts('*.fon')
     i = setfont(fonnam // 'h5w4b')
        XC = -B/5.0
```

```
      YC = H/2.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 21
      locy = xy.ycoord - 3
      CALL MOVETO(LOCX,LOCY,xy)
      WRITE(STR,'(F5.2)') H9
      call outgtext(STR)
      CALL VARROW(0.0,H-TB,B+B/5.0,1)
         XC = B+B/5.0
      YC = (H-TB)/2.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 21
      locy = xy.ycoord - 3
      CALL MOVETO(LOCX,LOCY,xy)
      WRITE(STR,'(F5.2)') H-TB
      call outgtext(STR)
      CALL VARROW(H-TB,H,B+B/5.0,0)
         XC = B+B/5.0
      YC = (H-TB+H)/2.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord
      locy = xy.ycoord - 3
      CALL MOVETO(LOCX,LOCY,xy)
      WRITE(STR,'(F5.2)') TB
      call outgtext(STR)
      CALL HARROW(0.0,B,H+H/8.0,1)
         XC = B/2.0
      YC = H + H/8.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 16
      locy = xy.ycoord - 5
      CALL MOVETO(LOCX,LOCY,xy)
      WRITE(STR,'(F5.2)') B
      call outgtext(STR)
      CALL HARROW(0.0,TOE,H-TB-TB/2.0,0)
         XC = TOE/2.0
      YC = H-TB-TB/2.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 30
      locy = xy.ycoord - 15
      CALL MOVETO(LOCX,LOCY,xy)
      WRITE(STR,'(F5.2)') TOE
      call outgtext(STR)
      CALL HARROW(TOE+TSB,B,H-TB-TB/2.0,1)
         XC = (TOE+TSB+B)/2.0
      YC = H-TB-TB/2.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 16
      locy = xy.ycoord - 5
      CALL MOVETO(LOCX,LOCY,xy)
      WRITE(STR,'(F5.2)') HEEL
      call outgtext(STR)
C
```

```
         XC = (TOE+TSB-TST+TOE+TSB)/2.0
      YC = -H/13.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 25
      locy = xy.ycoord - 5
      CALL MOVETO(LOCX,LOCY,xy)
      WRITE(STR,'(F5.2)') TST
      call outgtext(STR)
         XC  = -B/4
         YC  = H + H/6
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 20
         locy = xy.ycoord + 10
         CALL MOVETO(LOCX,LOCY,xy)
         WRITE(STR, '(A33)') 'Press <Enter> to End session'
         call outgtext(STR)
C
         XC  = 0.0
         YC  = 0.0
         CALL GETVIEWCOORD_W(XC,YC,XY)
         locx = xy.xcoord - 70
         locy = xy.ycoord - 43
         CALL MOVETO(LOCX,LOCY,xy)
         WRITE(STR, '(A33)') 'CANTILEVER WALL: DESIGN SKETCH'
         call outgtext(STR)

       END
```

APPENDIX D

COMPARATIVE STUDY

APPENDIX D

COMPARATIVE STUDY

D1. General

This section contains the results of a comparative study conducted to compare TWALL designs of cantilever retaining walls with the designs done manually by students of earth retaining structures design course (CE 419). The class consisting 34 students was asked to design 34 different cantilever retaining walls. Basically, three variables i.e., wall height, backfill soil friction angle ϕ and slope angle β were changed within the economical and practical range. The design included checks for wall sliding and overturning only. The students were not asked to check for bearing capacity failures because it was beyond the scope of CE 419 course. Then the same 34 cantilever walls were designed on TWALL.

D2. Results

A comparison of students and TWALL design is shown in Figures D-1 to D-4 and Tables D-1 to D-3. In general the results compare well. The comparison of recommended base lengths by TWALL and students are shown in Figure D-1. For walls below 15 feet, the recommended base lengths by TWALL and students compare very closely and the variation is within one feet. For walls above 15 feet TWALL recommends longer base as compared to that recommended by the students. For these walls, the students designs were safe for wall sliding and overturning but their designs failed in bearing capacity. TWALL recommended long base to ensure wall stability against bearing capacity failures.

The comparison of recommended heel lengths is shown in Figure D-2. The results are similar to that discussed above. Some of the students used longer heel than TWALL but their design resulted in a situation where upward pressure at the intersection of heel and stem exceeded the downward pressure on the heel and the point of maximum shear and moment shifted away from the intersection point toward the free end of the heel. Heuristics incorporated in TWALL limits heel length to avoid such situation and ensures that point of maximum shear and moment always remains the intersection point. Thus, the assumption that heel is designed as a cantilever beam remains valid.

Figures D-3 and D-4 show the comparison of TWALL and students sliding and overturning safety factors respectively. The results compared generally well. Small scatter of sliding safety factors show that wall sliding mostly governed the design. But for walls 20 feet and above, the bearing capacity governs the design as can be seen from Tables D-1 to D-3.

D3. Summary

Generally, TWALL designs of cantilever retaining walls compared well with the students designs. For walls below 15 feet sliding mostly governed the design but for walls above 20 feet, bearing capacity governed the design. In the present study, wall overturning was not critical because high wall friction was used that substantially reduces the horizontal force on the wall. Overturning can possibly governs the design when foundation soil is very strong as compared to the backfill or the wall is acted upon by a very high surcharge load. Very short toe can also result in overturning failures.

TWALL can be used as a design tool for the preliminary design of cantilever retaining walls and for checking the existing designs with confidence and reliability. TWALL can also be used as an educational software to demonstrate the capabilities of knowledge based expert systems for designs problem in geotechnical engineering.

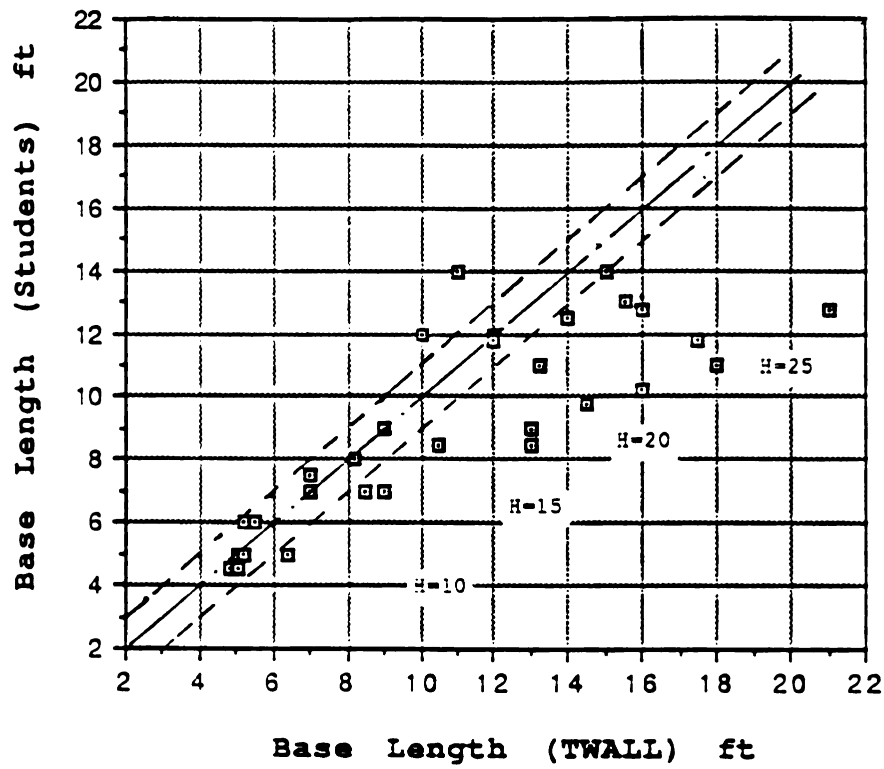


Figure D-1 Comparative study: base lengths designed by students (CE 419) versus TWALL

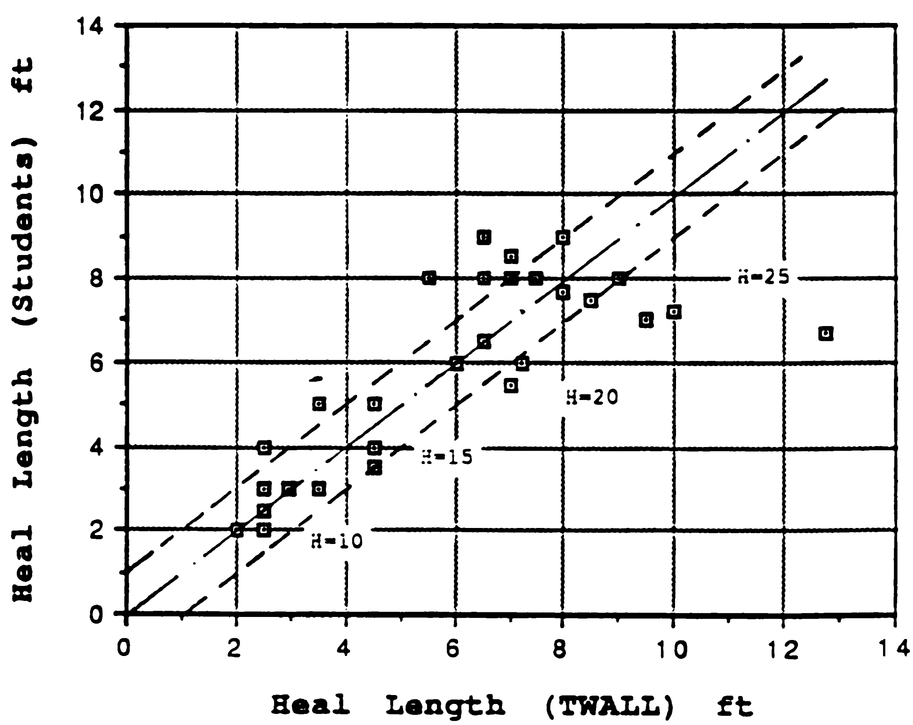


Figure D-2 Comparative study: heel lengths students (CE 419) versus TWALL

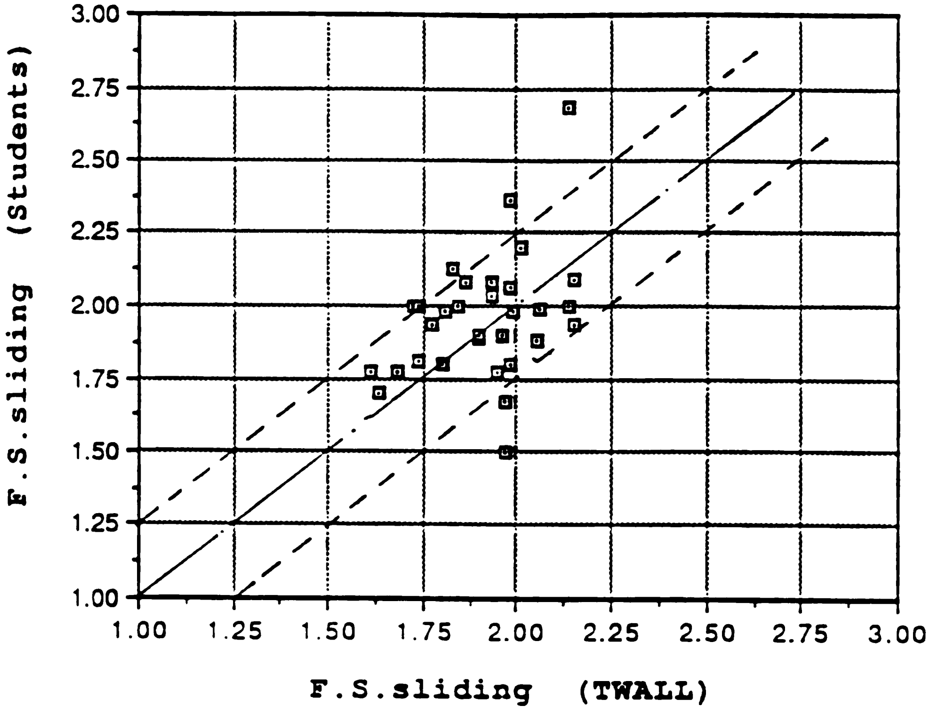


Figure D-3 Comparative study: sliding safety factors obtained by students (CE 419) versus TWALL

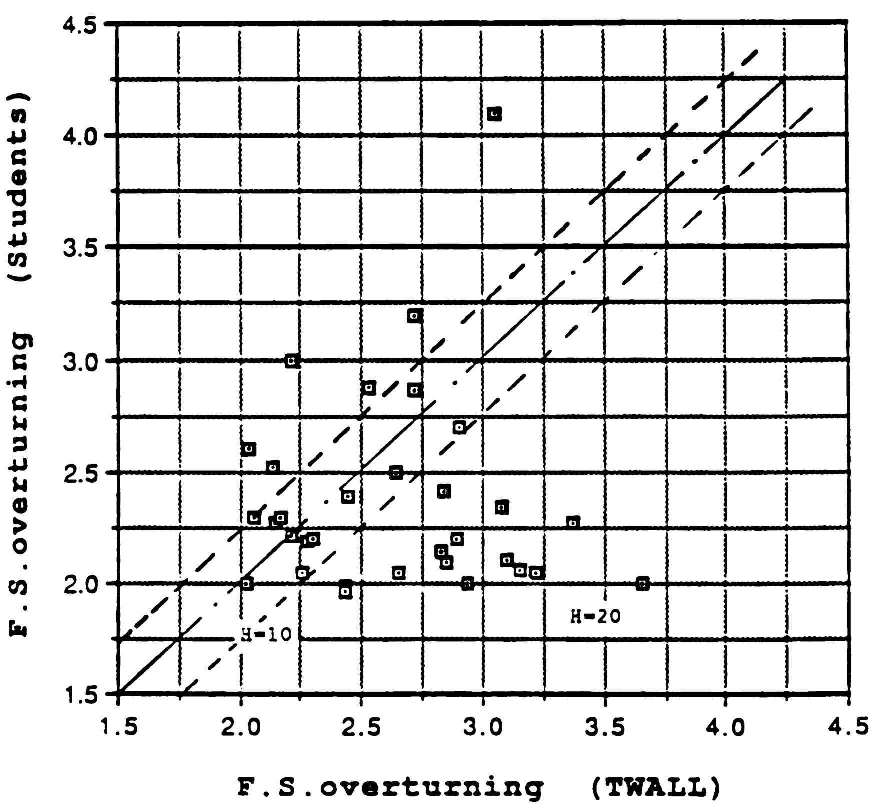


Figure D-4 Comparative study: overturning safety factors obtained by students (CE 419) versus TWALL

Table D-1 Comparison of TWALL designs with Students (CE419) designs (backfill slope=10 degrees).

Wall Parameters		Students Design			TWALL Design		
Wall Height ft	Misc.	Soil Friction Angle			Soil Friction Angle		
		30	33	36	30	33	36
10	Base Length ft	5.00	5.00	4.50	5.19	5.05	4.79
	Heel Length ft	3.00	3.00	2.00	2.50	2.50	2.00
	Toe Length ft	1.00	1.00	1.25	1.50	1.35	1.35
	F.S.sliding	1.81	2.36	2.00	1.74	1.98	2.14
	F.S.overturning	2.00	2.27	2.21	2.03	2.15	2.21
15	Base Length	7.00	-	7.00	8.50	-	7.00
	Heel Length	3.50	-	3.00	4.50	-	3.50
	Toe Length	1.50	-	3.00	2.75	-	2.22
	F.S.sliding	1.67	-	1.80	1.81	-	2.03
	F.S.overturning	1.96	-	2.20	2.43	-	2.30
20	Base Length	12.00	14.00	12.00	12.00	11.00	10.00
	Heel Length	8.00	9.00	8.00	6.50	6.50	5.50
	Toe Length	2.00	3.00	2.00	4.32	3.43	3.12
	F.S.sliding	2.13	1.88	2.68	1.83	2.05	2.14
	F.S.overturning	2.86	3.19	2.50	2.71	2.72	2.64
	F.S.bearing	-	-	-	3.06	3.07	3.14
25	Base Length	12.70	9.75	9.00	16.00	14.50	13.00
	Heel Length	8.00	6.50	6.00	9.00	6.50	7.25
	Toe Length	2.00	1.50	1.5	5.26	6.45	4.34
	F.S.sliding	1.77	1.98	2.09	1.95	1.81	2.15
	F.S.overturning	2.34	2.14	2.09	3.08	2.82	2.85
	F.S.bearing	-	-	-	3.11	3.06	3.07

Table D-2 Comparison of TWALL designs with Students (CE419) designs (backfill slope=15 degrees).

Wall Parameters		Students Design			TWALL Design		
		Soil Friction Angle			Soil Friction Angle		
Wall Height ft	Misc.	30	33	36	30	33	36
10	Base Length ft	6.00	6.00	4.50	5.50	5.19	5.04
	Heel Length ft	3.00	4.00	2.50	2.50	2.50	2.50
	Toe Length ft	2.00	1.00	1.00	1.81	1.50	1.35
	F.S.sliding	1.70	2.08	1.94	1.63	1.86	2.15
	F.S.overturning	2.3	2.52	2.04	2.06	2.13	2.26
15	Base Length	7.00	8.00	7.50	9.00	8.19	7.00
	Heel Length	4.00	5.00	5.00	4.50	4.50	3.50
	Toe length	2.00	1.5	1.5	3.20	2.40	2.21
	F.S.sliding	1.77	1.89	2.08	1.68	1.90	1.93
	F.S.overturning	1.99	2.39	3.00	2.43	2.44	2.21
20	Base Length	11.00	11.75	8.50	13.19	12.00	10.50
	Heel Length	7.66	8.00	6.00	8.00	7.00	6.00
	Toe length	2.00	2.00	1.50	3.90	3.84	3.46
	F.S.sliding	1.90	1.98	1.99	1.90	1.99	2.06
	F.S.Overturning	2.70	2.41	2.04	2.90	2.84	2.65
	F.S.bearing	-	-	-	3.07	3.24	3.05
25	Base Length	11.75	10.25	12.50	17.50	16.00	14.00
	Heel Length	7.25	7.50	8.50	10.00	8.50	7.00
	Toe Length	3.00	1.50	2.50	5.66	5.87	5.55
	F.S.sliding	2.28	1.82	2.20	1.93	1.98	2.01
	F.S.overturning	2.04	2.06	2.00	3.22	3.15	2.93
	F.S.bearing	-	-	-	3.08	3.08	3.15

Table D-3 Comparison of TWALL designs with Students (CE 419) designs (backfill slope=20 degrees).

Wall Parameters		Students Design			TWALL Design		
Wall Height ft	Misc.	Soil Friction Angle			Soil Friction Angle		
		30	33	36	30	33	36
10	Base Length ft	5.00	5.00	5.00	6.40	5.19	5.04
	Heel Length ft	3.00	3.00	2.00	2.96	2.50	2.50
	Toe Length ft	1.00	1.00	2.00	2.25	1.50	1.35
	F.S.sliding	1.77	2.00	1.80	1.61	1.72	1.98
	F.S.overturning	2.19	2.60	2.30	2.28	2.04	2.17
15	Base Length	-	9.00	-	-	9.00	-
	Heel Length	-	5.00	-	-	4.50	-
	Toe Length	-	2.00	-	-	3.21	-
	F.S.sliding	-	1.94	-	-	1.77	-
	F.S.overturning	-	2.88	-	-	2.53	-
20	Base Length	14.00	8.50	-	15.00	13.00	-
	Heel Length	9.00	5.50	-	8.00	7.00	-
	Toe length	3.50	2.00	-	5.60	4.77	-
	F.S.sliding	2.00	2.00	-	1.74	1.84	-
	F.S.Overturning	4.10	2.20	-	3.06	2.89	-
	F.S. bearing	-	-	-	3.07	3.11	-
25	Base Length	12.76	11.00	13.00	21.00	18.00	15.50
	Heel Length	6.70	7.00	8.00	12.76	9.50	7.50
	Toe Length	3.70	2.00	3.00	6.50	6.76	6.47
	F.S.sliding	1.50	1.90	1.67	1.97	1.96	1.97
	F.S.overturning	2.00	2.27	2.11	3.66	3.37	3.10
	F.S.bearing	-	-	-	3.01	3.02	3.10