# MOVEX: INTERACTIVE DESIGN OF BRACED EXCAVATIONS TO LIMIT GROUND MOVEMENTS

by

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(ABSTRACT)

The personal computer program MOVEX, a program for the design of structurally supported excavations to limit lateral ground movements in clay soils, was revised and updated. A key element in the program, the method of determining factor of safety against basal heave, was fully rewritten. Seven case histories were examined to evaluate the program capabilities in predicting movements.

Two important improvements to the program include adding allowances for possible anisotropic strength variations in the soil layers, and for wall movements caused by excavation before supports are added to the wall. The latter issue is relevant inasmuch as such movements are present in almost all excavations to one degree or another. The program output was also updated using a streamlined and more informative format. Disclaimer statements were added to certain areas to notify the user of program limitations. Movement calculation methods were improved by removing several errors and adding a linear interpolation feature which eliminates our earlier problem with jumps in

predictions as certain parameter horizons were passed. Finally, the Fortran program was reorganized and comment statements were added to provide a more flowing and readable style, and a new User's Guide was developed to reflect the new program.

## Acknowledgements

This thesis is dedicated to my parents, and the late .. They taught me to strive for excellence and to reach for ever higher goals. They have been wonderful, loving parents, and were always supportive of my various endeavors.

I would like to thank my husband, , whose undying patience and succoring helped me to complete my research with an intact psyche. Those who made graduate school an adventure include: my classmates and very good friends and ; also , , , , all of the Corps of Engineers guys, and my office-mate ; my non-geotechnical buddy , with whom I made my first road trip to Maine; and our neighbors and close friends .

I want to especially thank Professors Mike Duncan and Wayne Clough. Both provided valuable and stimulating classroom instruction in geotechnical engineering. They also provided time outside of class to answer my many and frequent questions. Mike Duncan was especially helpful as I was interviewing with various geotechnical consulting firms: he gave me wonderful advice on what to look for in an employer and guided me in my career choices. I very

much admire and respect Wayne Clough; he seems to have boundless energy and endless commitments, yet he had time to share his expertise in braced excavations with me as I worked on this thesis.

Others within the Civil Engineering Department that deserve recognition include Tom Brandon, who helped make computers less intimidating (and soil behavior more so), , , and last but not at all least, (I think they know how they helped me survive graduate school).

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# Chapter 1

## Introduction

Vertical sided excavations are often required in urban construction because of the declining amounts of space available for growth. Large basements, designed in order to provide expanded work space and parking areas in city buildings, are constructed in deep braced or tied-back excavations. Many transportation facilities and utility structures, such as subway stations, sewage tunnels and utility pipelines, are also constructed within such braced excavations. Because of the congested land area in larger cities, most deep excavations are constructed adjacent to existing structures and utilities. These structures can be damaged by ground surface settlements resulting from lateral wall movements during construction of braced excavations. Problems can range from cracked sidewalks and pavements, to damaged underground utility lines and enclosures, to costly building settlements. Growing concern over damage to adjacent structures, and the increased possibility of litigation, has lead to increased concern about surface and wall movements during construction of braced excavations.

The program MOVEX has been created to provide a means of estimating wall movements and surface settlements for supported excavations in clays. MOVEX is based on the simplified method developed by Mana and Clough (1981) and Clough (1985) in which wall behavior trends derived from field data and predictions by the finite element method were investigated. Mana and Clough concluded that wall movements are influenced by many factors, principal among which are factor of safety against basal heave, strut and wall stiffness, soil stiffness, excavation geometry, construction procedures, and workmanship. The method proposed by Mana and Clough was based on hand calculations. MOVEX was designed to automate the calculations on a personal computer, and allow readily for parametric studies that are valuable in design. The first version of MOVEX was developed by Sunami (1981). Since that time it has been modified by Goessling (1985), Smith (1986), and the present author (1987).

The four options available within MOVEX include: 1) enter the entire excavation geometry and stiffness, and MOVEX provides the maximum lateral wall movements at each excavation stage; 2) enter the excavation geometry and maximum allowable lateral wall movements, and MOVEX provides the required wall stiffness; 3) enter the excavation geometry, stiffness and maximum lateral wall movements, and MOVEX provides the required strut spacing; 4) enter the excavation geometry and maximum allowable lateral wall movements, and MOVEX provides the required strut stiffness. MOVEX also has an option which will provide the distribution of ground surface movements with respect to distance from the wall.

Several improvements were made to MOVEX in this thesis. Two optional design parameters let the user account for 1) anisotropic strength variations in the soil layers, and 2) cantilever movements incurred before first strut installation. Other changes made include reformatting and updating the generated output, printing Stage 1 movements, and printing the system of units used. Disclaimer statements were added to specific areas to notify the user of the program's limitations. The calculation methods were improved by adding a linear interpolation routine to more accurately estimate movements based on factor of safety against basal heave. The factor of safety against basal heave subroutine was also rewritten. Also, the Fortran program was reorganized and comment statements were added to provide a more flowing and readable style. The User's Guide was revised to include the added items.

This thesis describes the new MOVEX program through a chapter which discusses the basic concepts important to the behavior of supported excavations, chapters which detail the principles and methods used by MOVEX to evaluate factor of safety against basal heave, anisotropy, and cantilever effects, and a chapter with analyses of seven case histories. In each of the chapters which discuss methods used by MOVEX, example problems are provided to explain the concepts. The case histories provided were examined using the revised version of MOVEX, and the resulting predictions of maximum wall movements were compared to observed movements. The case histories are composed of three Chicago studies previously presented by Smith (1986), three Singapore studies from Broms, Wong, and Wong (1986) and one Singapore study from Wong (1987).

# Chapter 2

# Background

## 2.1 Introduction

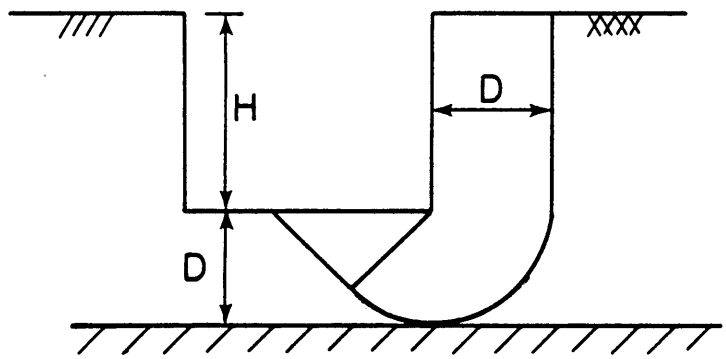
This chapter introduces the basic concepts important to the behavior of supported excavations, including the various methods for calculating the factor of safety against basal heave (FS) and concepts concerning movements of wall systems. The subject of earth pressures acting on excavations is outside the scope of this thesis; for further information on this topic, the reader is referred to Peck (1969), Terzaghi and Peck (1967), and Peck, Hanson, and Thornburn (1974).

## 2.2 Factor of safety against basal heave (FS)

Terzaghi (1943) proposed a method for evaluating the FS in a clay cut in terms of a shallow foundation bearing capacity problem. He suggested that the soil along the sides of the excavation acts as a uniform surcharge on the soil horizontally adjacent to the excavation bottom. The excavation base will heave when the surcharge loading exceeds the bearing capacity of the soil below the cut. The FS is

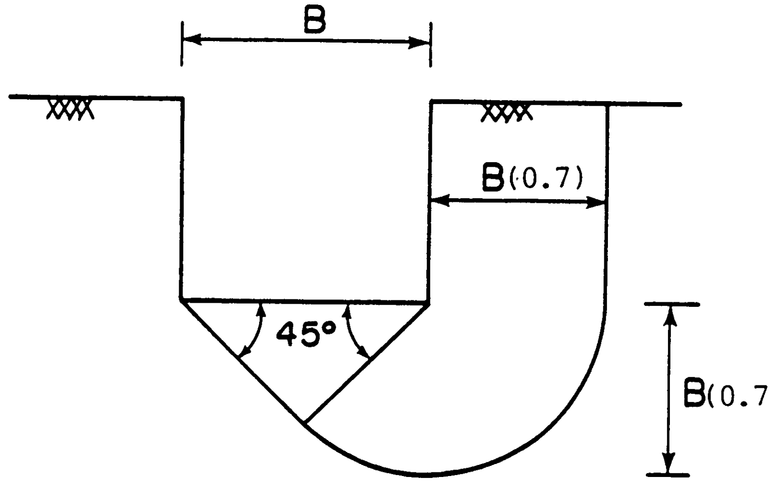
$$FS = \frac{\text{Bearing Capacity}}{\text{Surcharge Load}} = \frac{N_c}{Q}$$

The equations developed by Terzaghi for FS in homogeneous




$$FS = \frac{1}{H} \cdot \frac{5.7 s_u}{\gamma - s_u/D}$$

(a) D < B(0.7)




$$FS = \frac{1}{H} \cdot \frac{5.7 s_u}{\gamma - s_u/B(0.7)}$$

(b) D > B (0.7)

Figure 2.1- Factor of Safety Against Basal Heave (after Terzaghi, 1943)

clay soils are shown in Figure 2.1 where:

$S_u$ = undrained shear strength of the soil
B = excavation width
H = excavation depth
$\gamma$ = unit weight of the soil
D = depth to firm layer as measured from excavation bottom

Figure 2.1.a is applied when the ideal cohesive soil is underlain by a firm layer at a depth D below the excavation bottom, and $D < 0.7B$. Figure 2.1.b is for an ideal cohesive soil extending to a considerable depth below the excavation bottom.

Terzaghi's shallow foundation bearing capacity term, $N_c$, was later modified by Skempton (1951). Skempton suggested the bearing capacity factor for footings on clay is influenced by the three-dimensional shape of the foundation:

$$N_c = 5\ (1 + 0.2\ \frac{B}{L})\ (1 + 0.2\ \frac{D}{B}) \qquad (2.1)$$

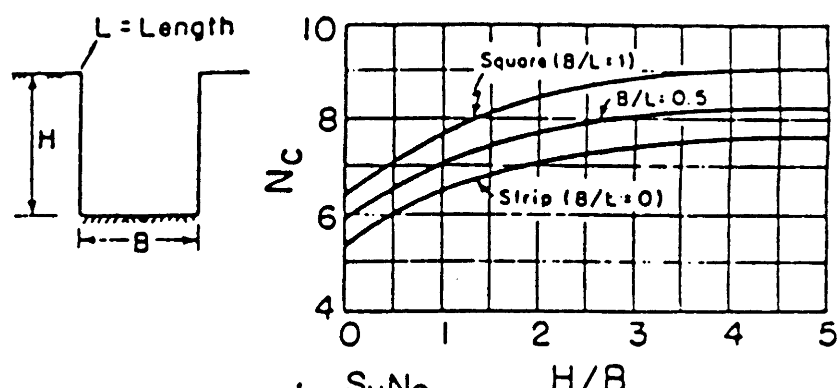
where: B = footing width
L = footing length
D = footing depth

Assuming that a shallow failure mechanism governs the basal heave problem, the depth term would be taken as zero. The bearing capacity term is then

$$N_c = 5\ (1 + 0.2\ \frac{B}{L}) \qquad (2.2)$$

Bjerrum and Eide (1956) conducted a study of 14 deep, narrow excavations in soft clay that had failed by basal heave. They concluded that the deep bearing capacity analysis applied in this case, and they applied the full Skempton bearing capacity factor directly to the analysis of basal heave of excavations, as shown in Figure 2.2. The bearing failure in this case is assumed to be confined to the area adjacent to and beneath the excavation bottom. Thus, the undrained soil strength used in the equation is expected to be that of the soil adjacent to and below the bottom of the excavation. It should be noted that Bjerrum and Eide (1956) indicated that the bearing capacity factors determined in this way appeared slightly conservative for sensitive Norwegian clays. Because the Bjerrum and Eide (1956) method allows for a larger bearing capacity factor than the Terzaghi method, the Bjerrum and Eide procedure generally gives a larger FS than the Terzaghi method. However, the Bjerrum and Eide procedure does not account for the effects of a nearby rigid base below the excavation (see Figure 2.1a), and it does not include an accounting for the effects of the strengths of the soils adjacent to the upper portions of the excavation.

In most standard references today, only the Bjerrum and Eide (1956) method is presented. However, because of the fact that different failure mechanisms actually occur, Clough (1985) suggests using the Terzaghi method for shallow, wide excavations (in which the ratio of depth to




Factor of Safety = $\frac{1}{H} \cdot \frac{S_u N_c}{\gamma}$

Bottom Heave Analysis for Deep Excavations (H/B > 1) -
BJERRUM & EIDE (1956)

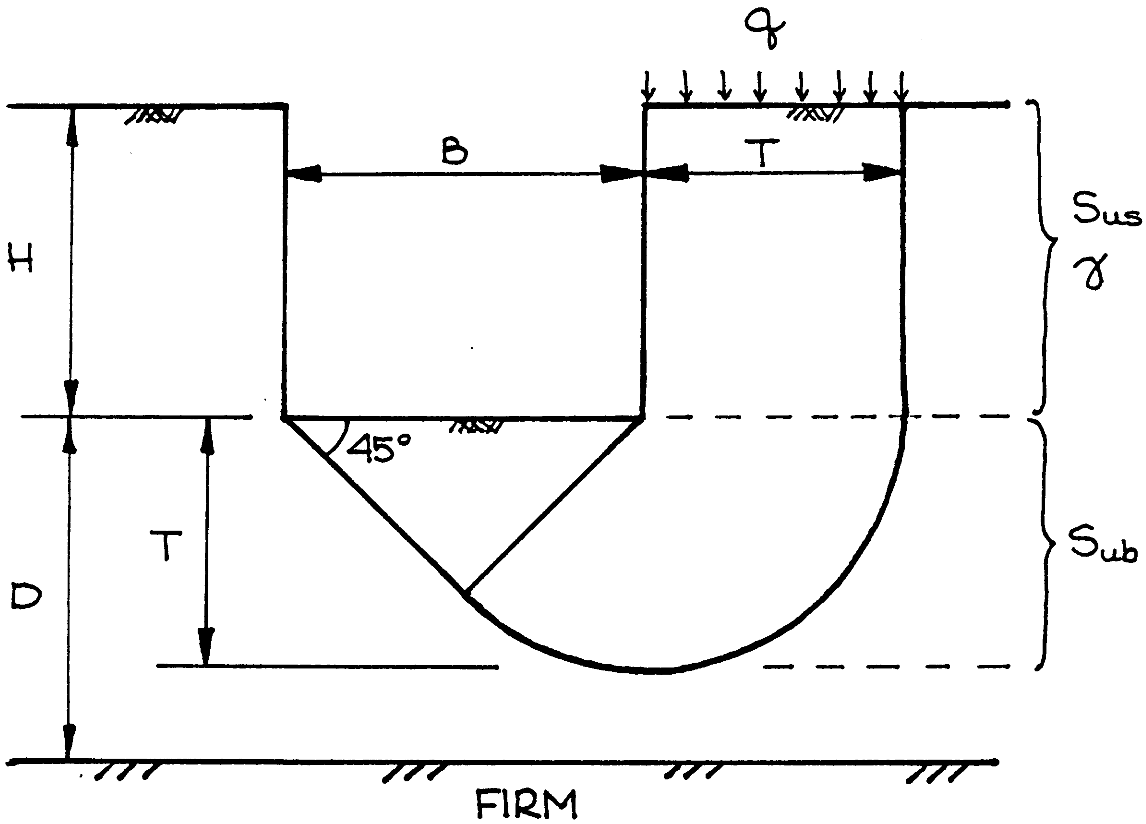
FIGURE 2.2 - Bearing Capacity Factor
(from Bjerrum and Eide, 1956)

width is less than or equal to one), and the Bjerrum and Eide method for deep, narrow excavations.

The FS calculation as described in the preceding paragraphs is for homogeneous, isotropic clays. When the soil profile is layered, when the shear strength increases with depth, and/or when a surcharge load is applied to the soil adjacent to the excavation, Duncan (1985) suggests making the Terzaghi type FS calculation as shown in Figure 2.3. It should be noted that the values of $S_{ub}$, $S_{us}$, and $\gamma$ are weighted averages. For example, a soil with i number of layers with thicknesses $h_i$, the average $S_u$ and $\gamma$ would be

$$S_u \text{ average} = \frac{\sum_{n=1}^{i} (S_{ui} h_i)}{\sum_{n=1}^{i} h_i} \qquad \gamma \text{ average} = \frac{\sum_{n=1}^{i} (\gamma_i h_i)}{\sum_{n=1}^{i} h_i}$$

A more detailed FS calculation can be derived from the method shown in Figure 2.3 to include the sliding resistance and/or bearing capacity provided by each soil layer. This calculation involves determining a sliding resistance sum along the vertical failure plane, a total vertical stress sum caused by the soils adjacent to the excavation, and a bearing resistance sum provided by the soils below the excavation bottom. This concept is illustrated in Figure 2.4. For soils in which the shear strength increases with depth, the value at the center of the layer should be used as the shear strength of that

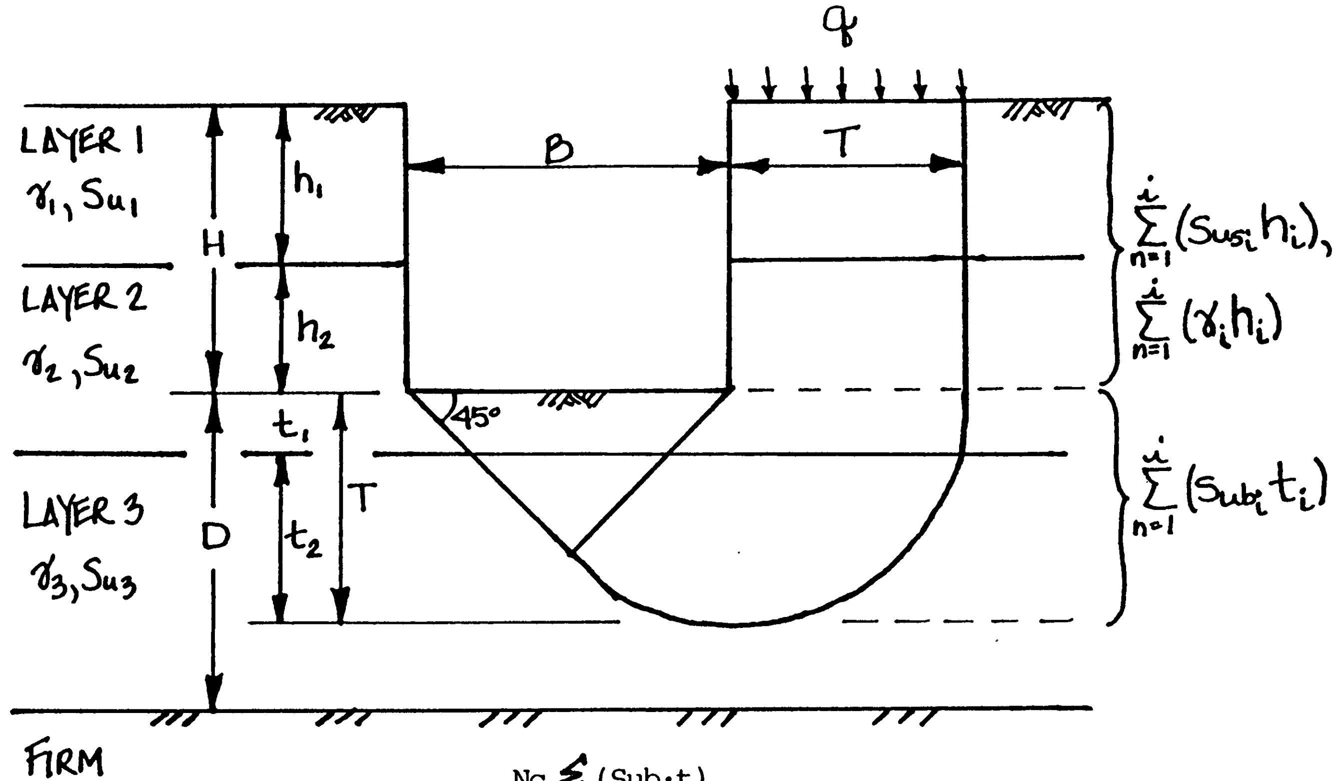



$$F = \frac{N_c\ S_{ub}\ T}{(\gamma H + q)T - S_{us} H}$$

If $D < 0.7B$, $T = D$
$D \geq 0.7B$, $T = 0.7B$

Sub = average Su below excavation
Sus = average Su along side of excavation
$\gamma$ = average total unit weight of soil along side of excavation
q = surcharge load

Figure 2.3: General Factor of Safety Calculation for Layered Soils (after Duncan, 1985)




$$F = \frac{N_c \sum_1 (Sub \cdot t)}{[\sum_1 (\gamma h) + q]T - \sum_1 (Sus\ h)}$$

If $D < 0.7B$, $T = D$ If $D \geq 0.7B$, $T = 0.7B$

Sus = Su along side of excavation
Sub = Su below excavation
$\gamma$ = total unit weight of soil along side of excavation
q = surcharge load

Figure 2.4: Detailed Factor of Safety Calculation for Layered Soils

layer. The procedure shown in Figure 2.3 is preferable for hand calculations, a more exact accounting as shown in Figure 2.4 can be accommodated in computer applications. It is the latter method which is used in MOVEX, as explained in Chapter 3 of this thesis.

Clough and Hansen (1981) showed that strongly anisotropic clays may have actual basal heave factors of safety as much as 50% lower than the predicted factors of safety computed assuming soil isotropy. In order to compensate for this effect, they modified the FS using an anisotropic strength bearing capacity factor, $N_c^*$, in the place of $N_c$. A broader discussion of anisotropic soils and related calculations follows in Chapter 4.

In most cases, the FS in clay soils decreases as the excavation is deepened. However, when a firm layer is at or below the base of the excavation, the FS will first decrease with depth, and then increase once the effect of the firm layer is felt. As Mana and Clough (1981) pointed out, the minimum FS is what most influences maximum wall movements. Since the minimum FS occurs just before the influence of the firm layer is felt, this is the value which governs supported wall system displacements.

## 2.3 Trends of movements of supported excavations in clay

A supported excavation is created in a sequential process. First, the wall is installed by any one of several techniques. Examples include driving interlocked sheetpiles or digging a trench and casting in place a concrete slurry wall. Next, an initial excavation is made to the depth of the first support level, and then the support, usually a brace or tieback, is installed. This is followed by more excavation to the level of the next support, and then the process repeats until the full depth is reached. Terzaghi (1936) first noted that the wall movement pattern in this situation is different than that for conventional retaining walls. Where the conventional wall translates or rotates about its toe, the supported excavation retention wall tends to rotate about its top. This is one of many differences between the conventional retaining wall system and that of the supported excavations retention system.

Using finite element techniques, Clough and his co-workers have been able to analytically simulate the behavior of the supported excavation wall system. The predicted pattern of movements for a braced wall in a deep deposit of soft clay is shown in Figure 2.5. This figure clearly shows the rotation of the wall about its top as was suggested by Terzaghi from field evidence. At the ground

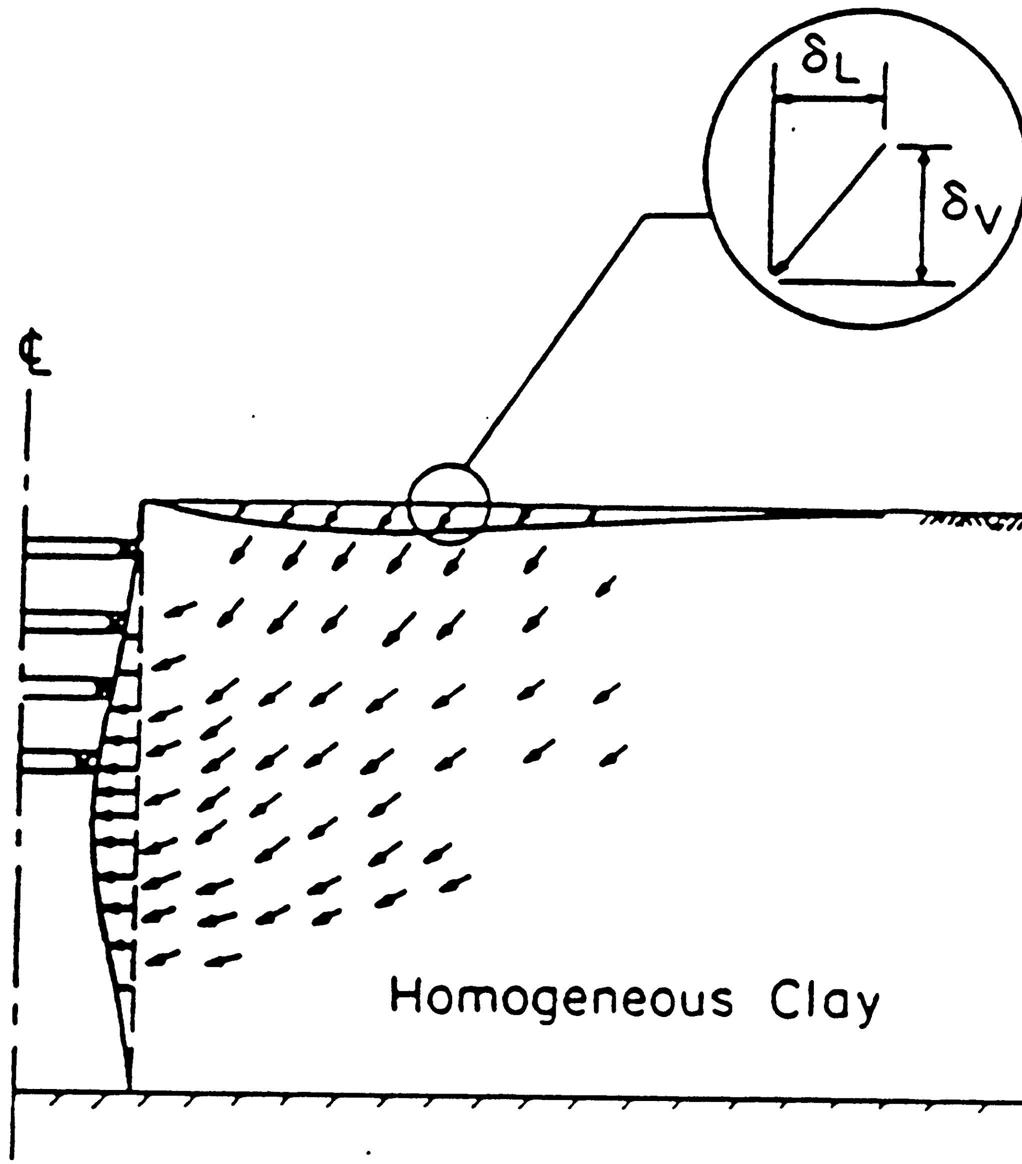
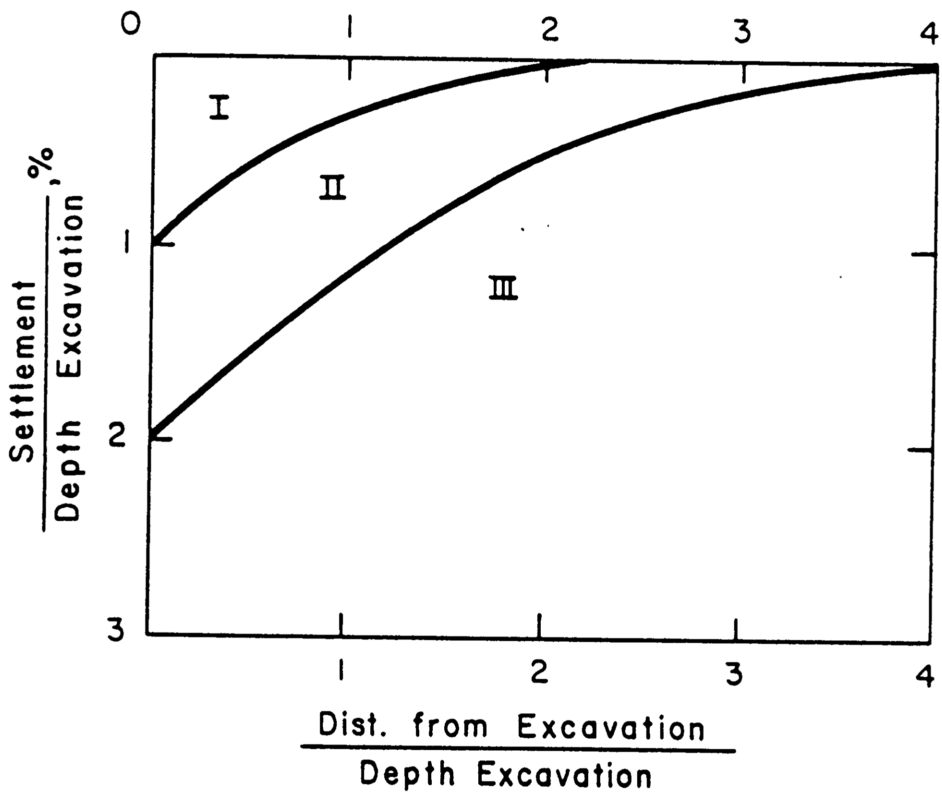



FIGURE 2.5 - General Movement Trends Around Braced Cuts (from Clough, 1985)

surface, the soil moves with vertical and lateral components.

Peck (1969) was the first to quantify the movements of the ground surface behind a braced wall in clays (Figure 2.6). His results are presented in a nondimensional form, with the axes, settlement of the ground surface plotted against distance from the excavation, divided by excavation depth. The results show that the movements can be expected to increase with decreasing strength of the clay, and with increasing depth of clay below the excavation. The data base for this plot was obtained from projects in Chicago.

The dimensionless Peck plot does not attempt to quantify the effects of many of the parameters that are known to influence braced wall movements. In part, this is due to the relatively limited data base that was available in the late 1960's. Since that time, there have been many developments in excavation wall technology, and instrumentation has been introduced that makes it much easier to accurately monitor excavation movements. A review of a more complete information base led Clough (1985) to compile a list of the more important parameters that have an influence on excavation support system movements as shown in Table 2.1. Of the 25 parameters shown, Clough (1985) noted that only about half were under the control of the designer. For this reason, the prediction of excavation support system movements is best




I - Sand and Soft to Hard Clay, Avg. Workmanship

II - Very Soft to Soft Clay

1. Limited Depth of Clay Below Bott. Exc.
2. Significant Depth of Clay Below Bott. Exc., But $N_b < N_{cb}$*

III - Very Soft to Soft Clay to a Significant Depth Below Exc. Bott. and $N_b > N_{cb}$

* $N_b$ = Stability No. Using C "Below Base Level" = $\frac{\gamma H}{C_b}$
$N_{cb}$ = Critical Stab No. for Basal Heave

Figure 2.6: Ground Surface Movements behind Braced Walls in Clays (from Peck, 1969)

Table 2.1

Major Factors Affecting Movements of Supported Excavations
(from Clough, 1985)

1. Excavation depth
2. Excavation geometry - width, shape, berms, symmetry
3. Duration of excavation
4. Construction within excavation
5. Wall stiffness
6. Tie-back or brace stiffness
7. Support spacing
8. Type of support connections
9. Amount of preload
10. Preload maintenance procedures
11. Soil strength, sensitivity, and stiffness
12. Soil stratification
13. Soil property variation with loading direction
14. Presence or absence of rigid base below soil strata
15. Initial groundwater level
16. Groundwater control system
17. Wall permeability
18. Potential of ground water movement
19. Support system construction sequence
20. Wall installation technique
21. Surcharge behind wall
22. Quality of workmanship
23. Weather
24. Site topography
25. Consolidation due to dewatering

seen as an attempt to predict the maximum displacement likely, since the actual displacements vary from point to point on any one job. It has to be presumed that the wall system will be constructed using good practices, since if this is not true, the wall and soil movements can be significantly increased over those expected. Factors such as poor brace to wall connections, overexcavation below brace or tieback levels, surcharge behind the walls, and drainage through the walls can increase wall movements.

Clough (1985) pointed out that the FS and system stiffness are the most important parameters influencing system movements for well constructed systems. He proposed the curves in Figure 2.7 to relate maximum lateral wall movements to the FS and system stiffness. It is important to note that the correlations are based on the Terzaghi type FS since this FS is considered as a more consistent index to excavation movements than the Bjerrum and Eide FS. Figure 2.7 provides the basis for the method with which MOVEX predicts lateral wall movements. The terms used to define the nondimensionalized system stiffness along the x-axis in Figure 2.7 are

E = modulus of elasticity of the wall
I = moment of inertia of the wall
$\gamma_w$ = unit weight of water
havg = average strut spacing.

Note that strut spacing enters as raised to the fourth power. Thus, the system stiffness is sensitive to this

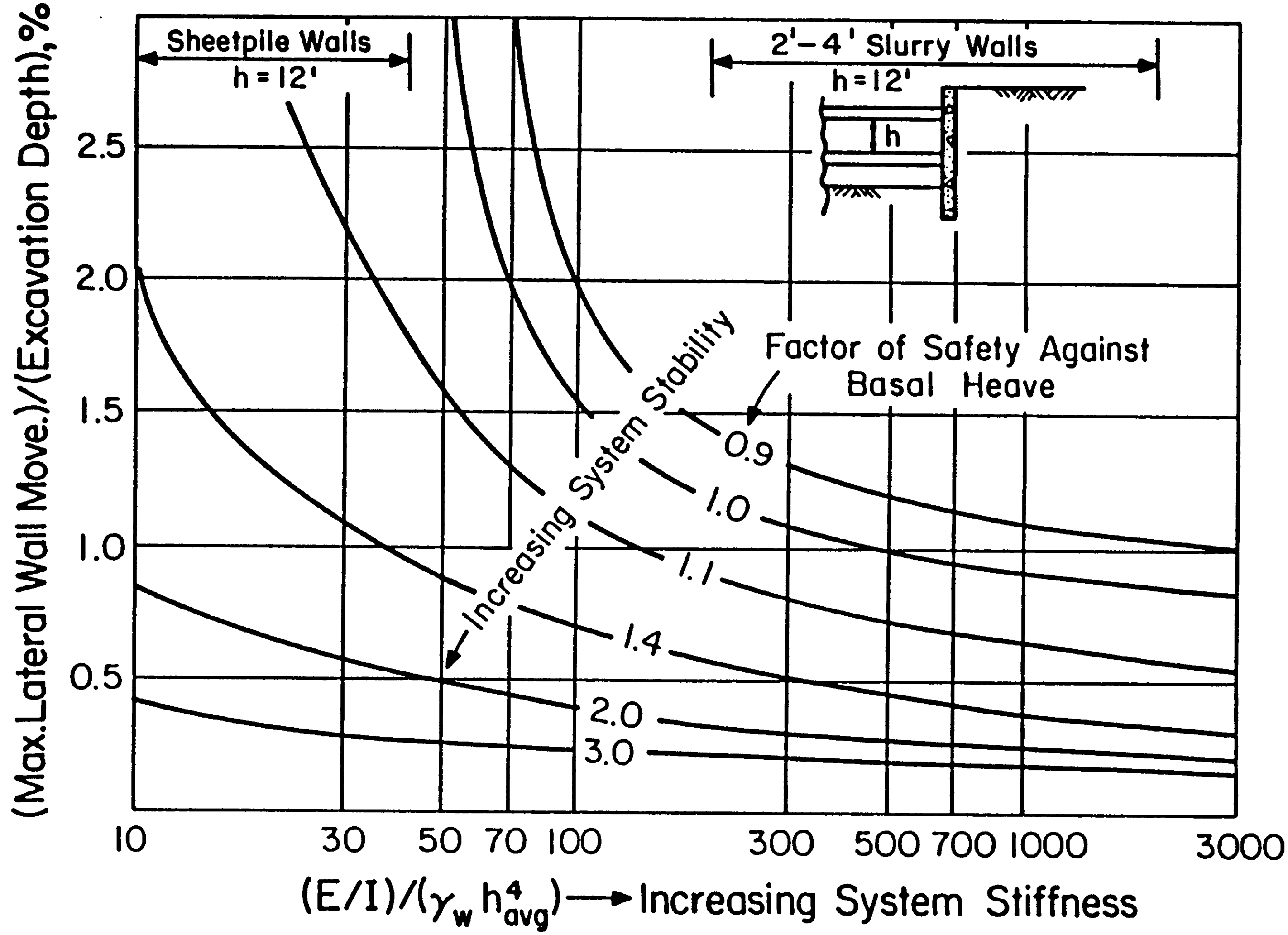



Figure 2.7: Relationship between Factor of Safety, System Stiffness, and Wall Movement (after Clough, 1985)

parameter. Figure 2.7 shows that all walls in clay, regardless of stiffness, will experience some lateral wall movements. As one should expect, the amount of movement increases with decreasing system stiffness and with decreasing FS. Mana and Clough (1981) provide several modification factors, described in Table 2.2, which allow the designer to also include the effects of other parameters on wall movements, such as strut stiffness, depth to firm layer, and excavation width. The final predicted value of maximum lateral wall movement is obtained by multiplying the value read from Figure 2.7 by the appropriate modification factors.

The strut stiffness value used in wall movement calculations should be the effective strut stiffness ($K_E$) rather than the ideal strut stiffness ($K_i$). The ideal strut stiffness is defined as

$$K_i = \frac{AE}{L}$$

where A = strut cross-sectional area
E = strut modulus of elasticity
L = strut length

The ideal strut stiffness only applies when the proper jacking and preloading techniques have been used to eliminate all slack in the excavation bracing. Slack in the bracing system and poor preloading procedures can cause $K_E$ to be significantly less than $K_i$. Hansen (1981) devised the curve shown in Figure 2.8, which shows the tendency of

Table 2.2

Alpha Factors for Evaluating Maximum Predicted Wall Movements
(after Mana and Clough, 1981)

| Alpha Factor | Approximate Range of Values | Parameter of Influence |
| --- | --- | --- |
| $\alpha_S$ | 0.75-1.2 | strut stiffness & spacing |
| $\alpha_D$ | 0.62-1.0 | depth to firm layer |
| $\alpha_B$ | 1.0-1.8 | excavation width |

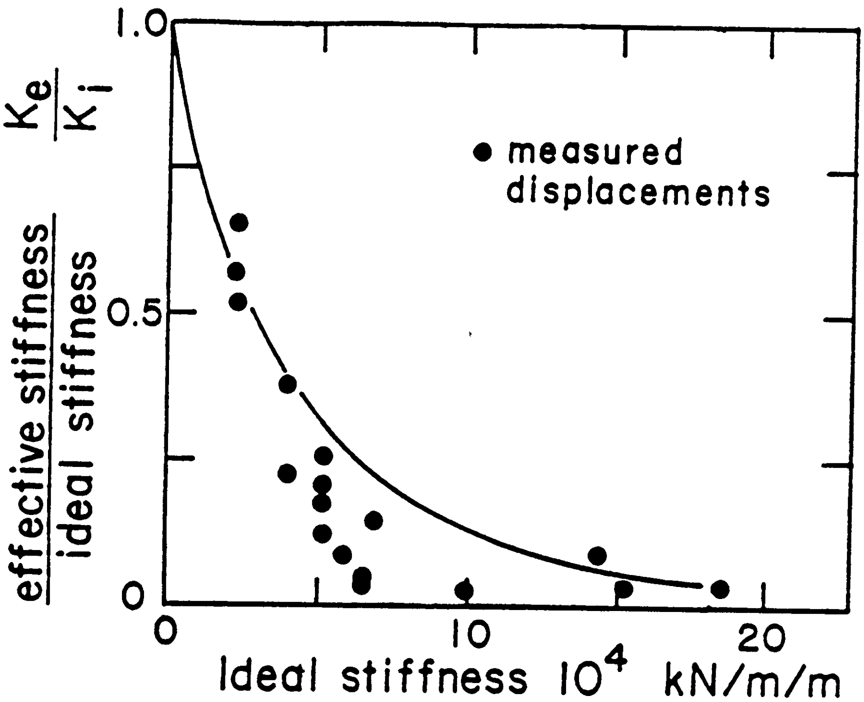



FIGURE 2.8 - Effective versus Ideal Strut Stiffness (from Hanson, 1981)

very stiff struts to have diminishing returns in terms of the effective stiffness demonstrated. In applying the design procedure given in this thesis, the user should evaluate the effective strut stiffness from Figure 2.8 and use $K_E$ in all places where strut stiffness is required.

The underlying motive for rigorous analyses of supported excavations is the evaluation of surface movements and their possible effects on adjacent structures and utilities. The curves presented by Peck (1969) represented the data available at the time for braced sheet pile and soldier pile walls (Figure 2.6). Since 1969, numerous studies of excavation behavior have been published, which have led to a greater understanding of the nature of wall and soil movements. O'Rourke (1981) and his colleagues examined patterns of lateral and vertical soil movements and determined that both components cause damage to structures. While there is an accurate database of lateral wall movements in the literature, there exists a lack of accurate field data on lateral and vertical surface movements. Vertical settlement data is collected much more frequently than lateral soil movement data, but even so, it is often obtained by the contracting force and is infrequently published.

Because lateral soil movements can cause as much damage to structures as settlements, the small amount of available field data led Clough and his co-workers to examine them with the use of the finite element method. The problem evaluated was a braced sheetpile wall in an undrained clay soil, in which several parameters, including the number of struts, undrained shear strength of the clay, thickness of the clay deposit, and excavation depth were varied in order to provide a full range of data (Mana, 1978). The movement vectors shown in Figure 2.5 were determined from this study.

Clough (1985) further analyzed the lateral and vertical movement components at the ground surface. In Figure 2.9, the components were isolated and plotted against distance from the edge of the excavation divided by excavation depth. The top set of plots is for a soil with a clay strength high enough to maintain a FS of 2.3 to the full excavation depth. With this high FS, the movements in the lateral and vertical directions show similar magnitudes, although the maximum lateral movement occurs further from the excavation. The lower set of curves in Figure 2.9 are for soil strengths low enough to cause a FS of 1.05 at the full excavation depth. In this case, the maximum vertical movements are shown to be about twice as large as the lateral movements, and they occur much closer to the excavation as compared to the maximum lateral movements, and to the maximum vertical movements shown for the FS equal to 2.3 case. The large vertical movements close to the wall reflect the initiation of a deep seated

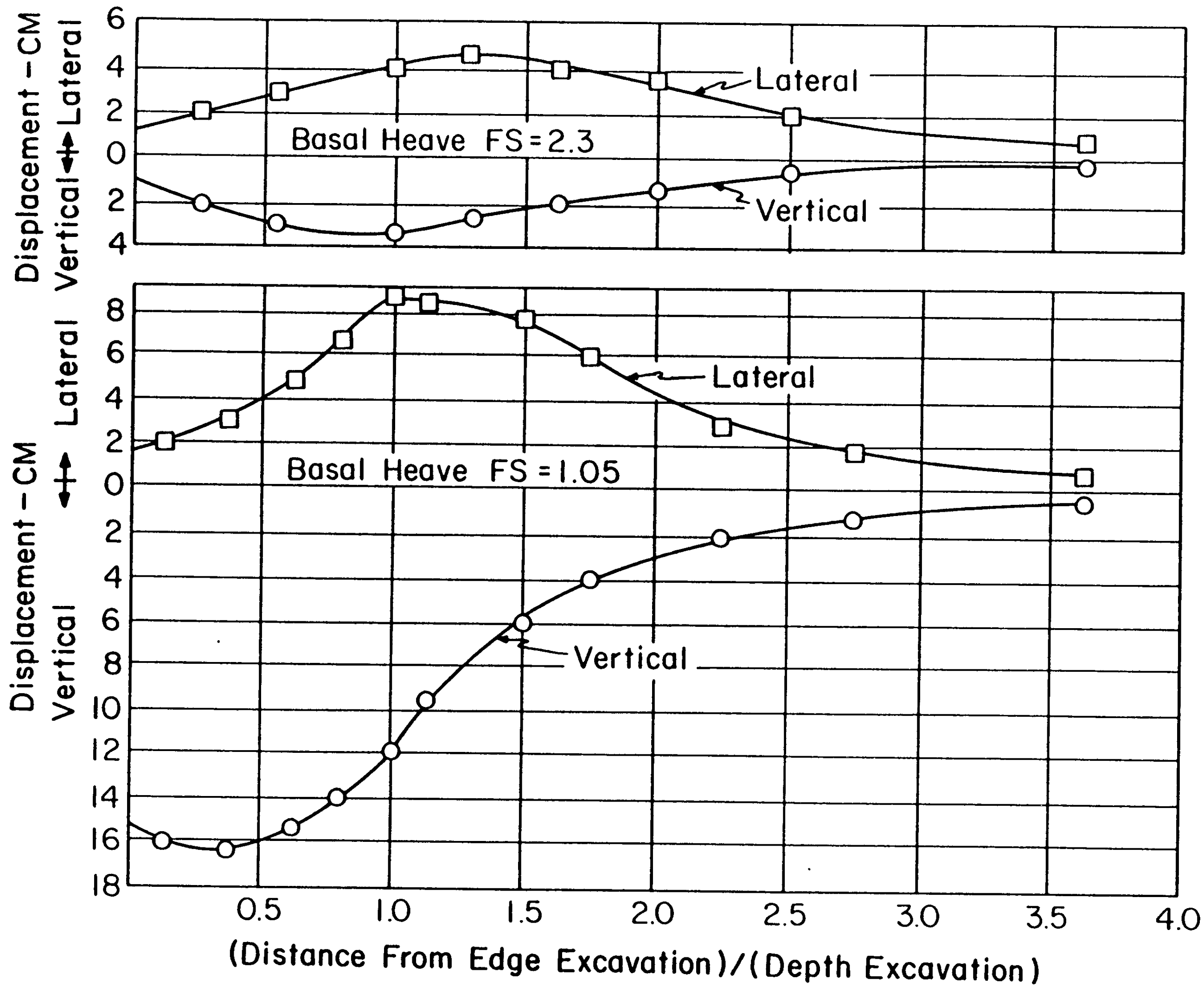



Figure 2.9 - Distribution of Vertical and Lateral Ground Movement (from Mana and Clough, 1981)

failure mechanism associated with basal heave at the lower FS. The lateral movements also show larger movements closer to the wall for a lower FS.

It has been determined that the lateral and vertical surface movements adjacent to an excavation show consistent trends when they are normalized. In Figure 2.10, the pattern of movement is shown to be a function of the FS and the distance from the excavation. The plot is nondimensionalized by dividing the vertical movement by the maximum settlement, and by dividing the distance from the excavation by the maximum depth of the excavation. According to Clough (1985), the maximum settlement for well constructed supported excavations ranges from 0.6 to 1.2 times the maximum lateral wall movement, and for practical purposes the two values can be assumed to be equal. Thus, if the maximum wall movement is predicted, the entire settlement profile for the ground surface behind the wall can be estimated. The curves of Figure 2.11 show the pattern of lateral surface movements as a function of FS and distance from the excavation. This plot is normalized in terms of lateral surface movements divided by the maximum lateral wall movement, and distance from the excavation divided by excavation depth as before. Using Figures 2.10 and 2.11, the entire surface movement profiles can be estimated. This method is that utilized by MOVEX to evaluate the distribution of ground surface movements.

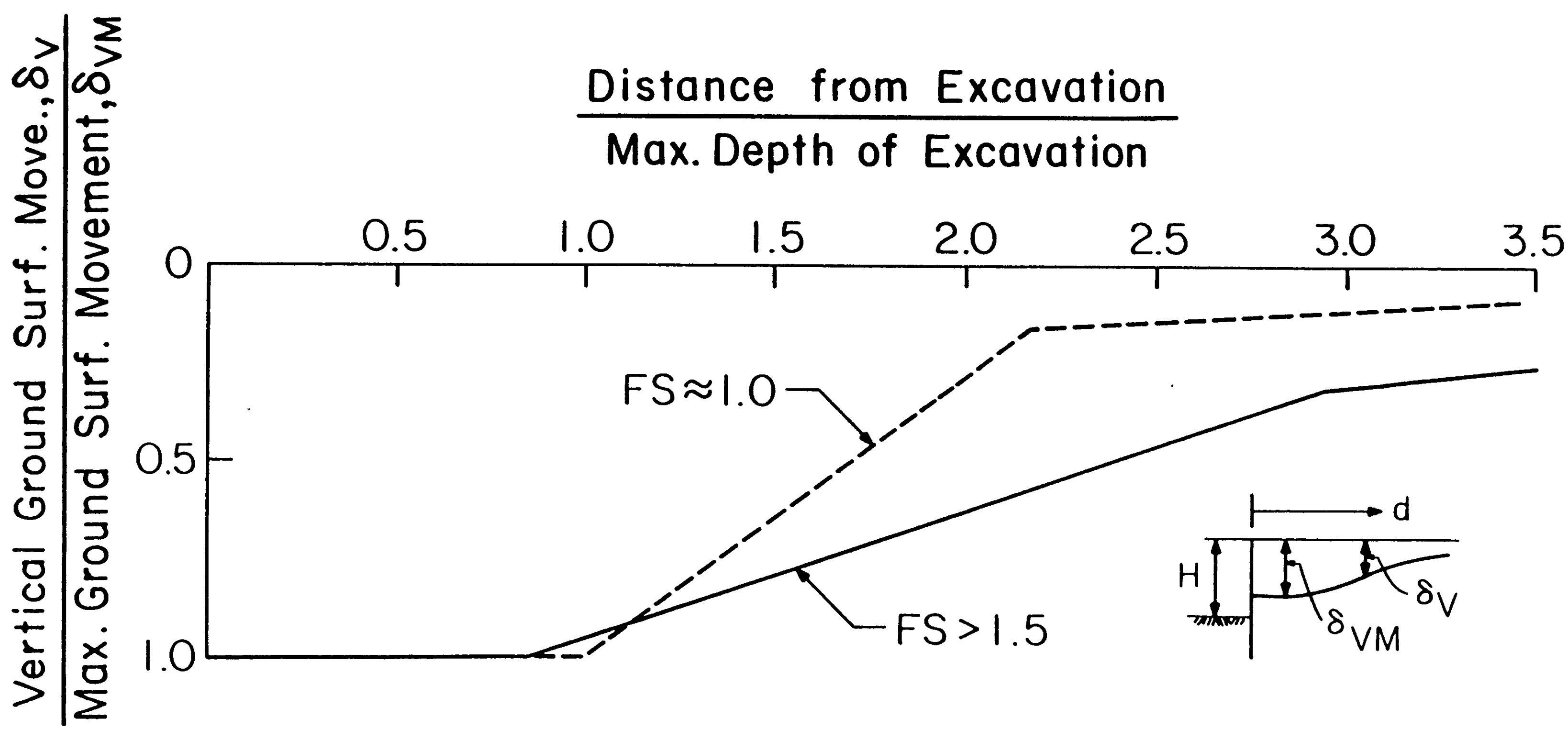



Figure 2.10 - Distribution of Vertical Ground Movement (from Mana and Clough, 1981)

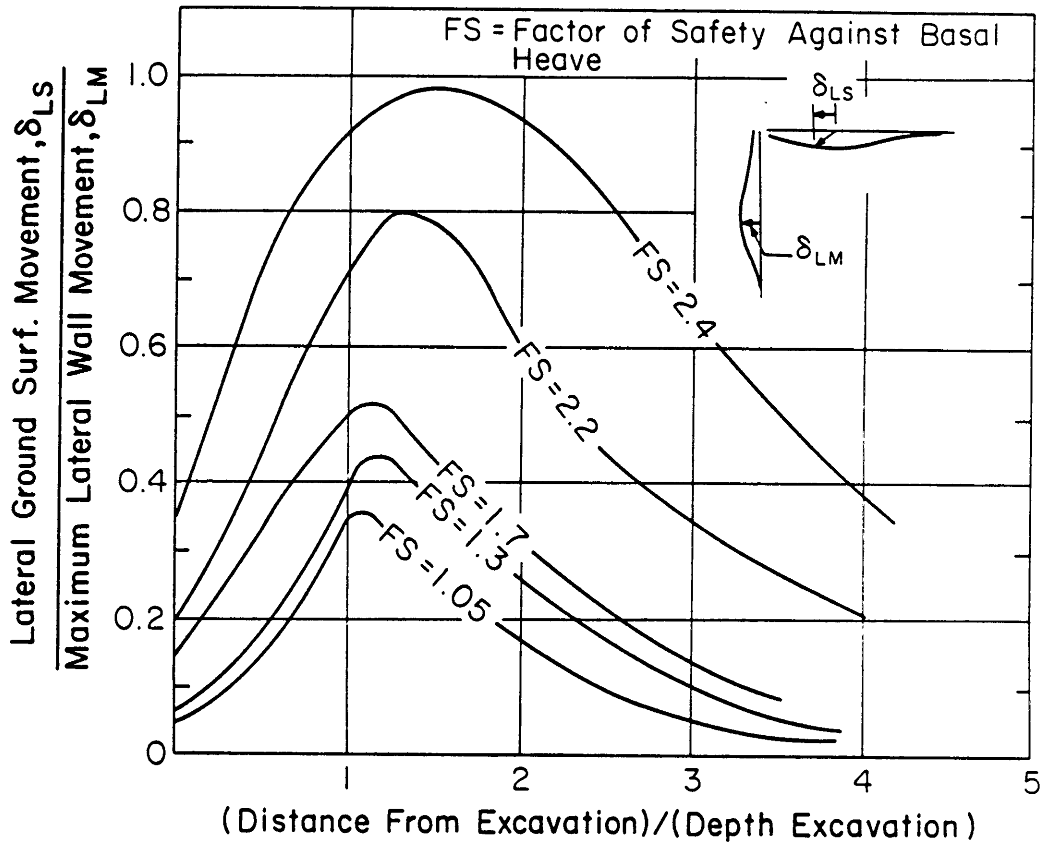



Figure 2.11 - Distribution of Horizontal Ground Movement
(from Clough, 1985)

## 2.4 Trends of cantilevered wall movements

Peck (1969) and Clough and Davidson (1977) note that increased wall movements and ground settlements are caused by late installation of the first level of wall supports. Unfortunately, in the construction of braced excavations, the installation of the first strut level is often delayed; the reasons for such delays may vary, but they are usually the result of poor construction practice, access problems, or demolition of deep old basement structures. Figure 2.12 compares the final wall movements of two excavations in Chicago constructed in similar soil conditions. The Case 1 wall underwent initial cantilever movements of one inch. Late installation of the wall supports at Case 2 led to 4 inches of cantilever movements, and larger final movements for the wall at full excavation depth.

The wall behavior pattern is such that the movement associated with the cantilever effect decreases approximately linearly with depth to some hinge point, below which the cantilever effect is zero. If this amount of movement is removed, the remaining wall movements are essentially those associated with the wall constructed without the initial cantilever. This effect can be seen in Figure 2.13, in which the cantilever effect estimated for Case 2 was removed, and the resulting wall profile plotted next to the Case 1 wall. For this example, the amount of cantilever removed at the top of the Case 2 wall is three

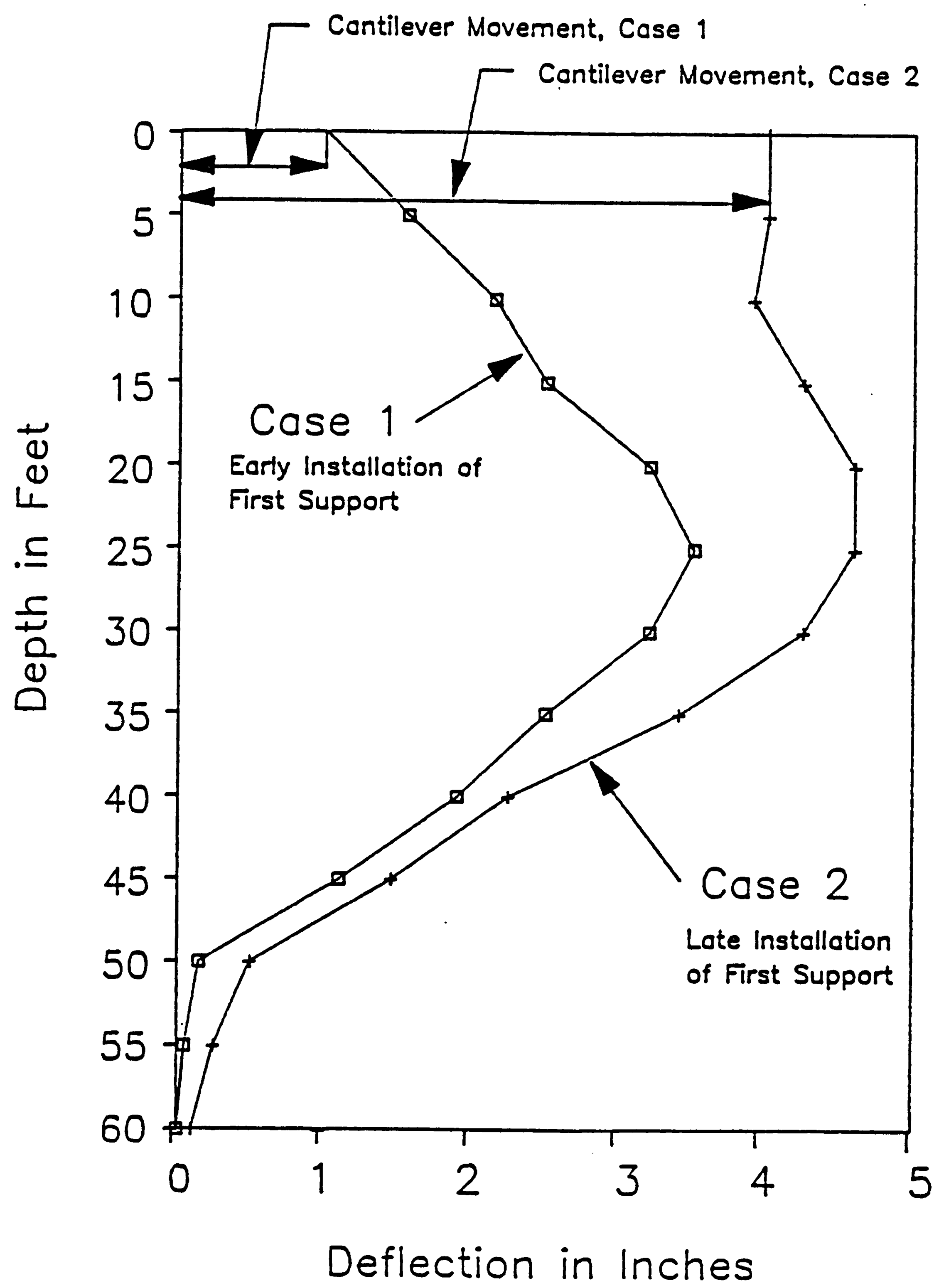



Figure 2.12 - Final Wall Movements of Two Excavations in Chicago (after Smith, 1986)

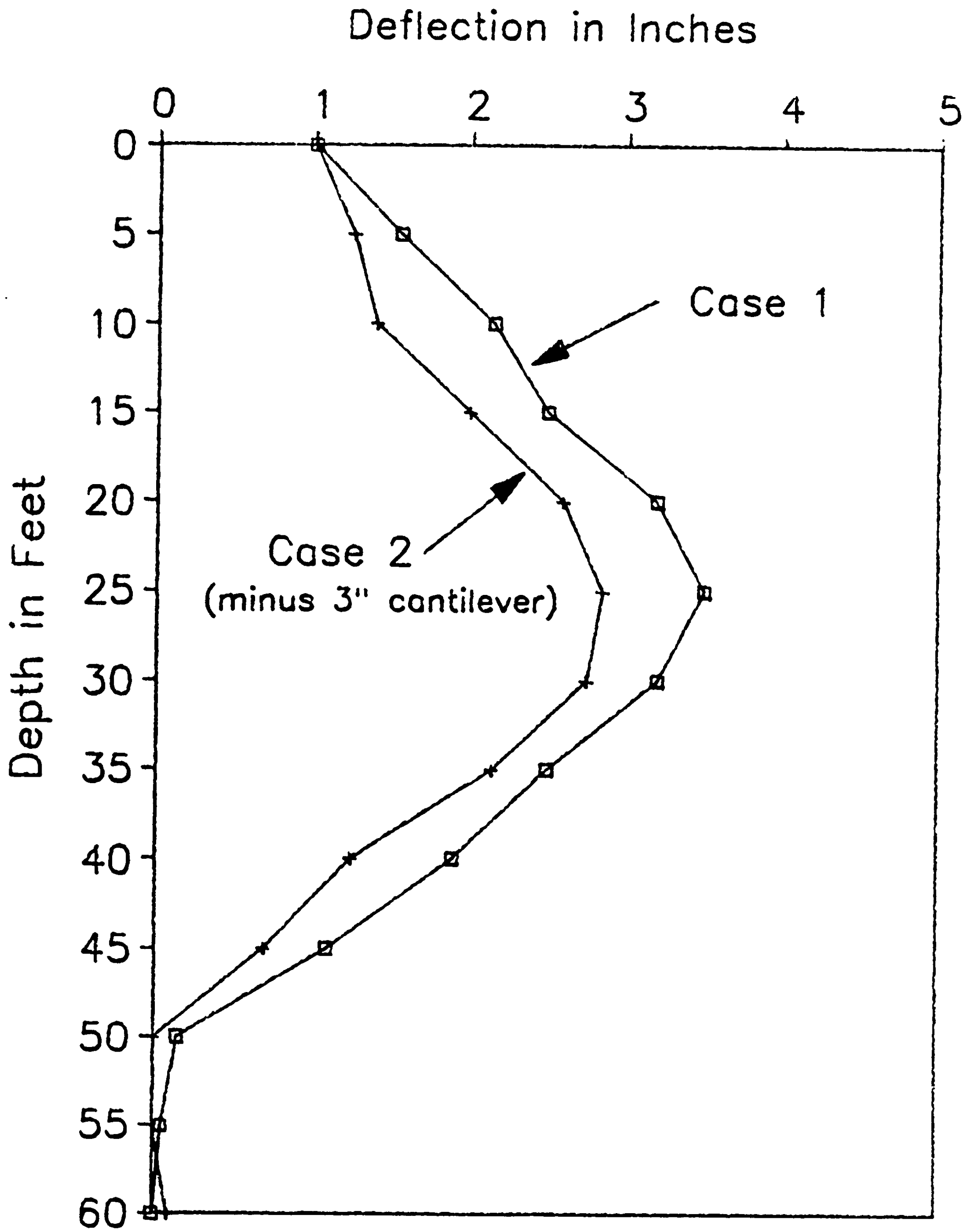



Figure 2.13 - Profiles of Two Walls in Chicago, Manipulated to show Equal Amounts of Cantilever Movement

inches. The amount removed with depth decreases linearly, such that at the depth of 60 feet, where the cantilever effect is zero. The wall profile of remaining movements shows a pattern very similar to that of the Case 1 wall, and can be considered as the profile the wall would have shown had the cantilever been limited to one inch. Similarly, the effects of delaying installation of the first support can be evaluated by adding a cantilever movement during analysis, and comparing the resulting wall and settlement profiles to those of the wall analyzed without the cantilever. A further discussion of the method used to evaluate the effects of cantilever movements is presented in Chapter 5 of this thesis.

# Chapter 3

## Basic Factor of Safety Against Basal Heave and Movement Calculations in MOVEX

### 3.1 Introduction

This chapter describes the methods with which the new version of MOVEX calculates FS, wall movements, and surface movements for a supported excavation in isotropic clay with nominal cantilever wall movements. Two sections provide suggestions for design use of the program, including choosing the soil strength parameters, and predicting wall movement and surface settlement profiles. Examples are presented to illustrate these methods.

### 3.2 MOVEX calculations of FS

In the program MOVEX, the FS is based on the Terzaghi approach since this was used as the basis of the support system movement correlations incorporated in the program. FS is evaluated at each excavation stage, and also at points between excavation stages. The excavation stages are defined by the strut levels, and thus stage 1 is at the level where strut 1 is installed. The FS is not calculated for stage 1 if the first strut is installed at zero depth, but the FS is still evaluated between stage 1 and stage 2. MOVEX checks the FS between stages by simulating the excavation between struts in ten steps. The program does this by checking the FS in increments of one-tenth of the distance between struts. The reason for checking the FS incrementally as the excavation proceeds is to establish the minimum FS, the factor which most influences movements.

MOVEX reports both the FS at each excavation stage and the minimum FS between stages. The minimum FS is used in subsequent calculations of wall movement. MOVEX calculates the FS at each depth with the equation

$$FS = \frac{N_c \sum_1 (S_{ub} \cdot t)}{[\sum_1 (\gamma \cdot h) + q]\ T - \sum_1 (S_{us} \cdot h)}$$

where all of the terms are illustrated in Figure 2.4. The bearing capacity factor, $N_c$, is calculated with equation 2.2, which includes an accounting for the excavation shape in the analysis. The calculation of FS performed by MOVEX follows the procedure shown in Figure 2.4.

### 3.3 Suggested use of soil strength parameters

The undrained shear strength of clay soils is typically only approximately known for supported excavation design. In many cases, because these structures are often temporary, the soil investigation is only cursory. In other cases, there can be sample disturbance effects. Generally, these situations lead to to the use of a conservative estimate of the undrained shear strength. In order to understand the possible range of movements and FS of an excavation, reasonable high and low undrained shear strength estimates can be used for each soil layer. With these values several passes of MOVEX can be made. Also, in the case where the soil profile is erratic over the site, the depth to firm layer can be varied to evaluate its effect on the predicted movements.

MOVEX is based on excavation behavior in clay soils, where FS is important to behavior. Excavations in sand are not dependent on FS, rather they are dominated by the relative density, or friction angle, of the sand, and construction factors. Thus, MOVEX should not be used for excavations in sand. However, many predominantly clay soils contain sand layers, and the effects of these layers can be approximately evaluated by MOVEX. To include the strength of the sand layer, an "equivalent cohesion" should be calculated for the sand layer using equation 3.1:

$$S_u = \sigma_h' \tan\phi \qquad 3.1$$

where $S_u$ = "equivalent cohesion" of the sand layer
$\sigma_h'$ = horizontal effective stress in the sand layer
$\phi$ = angle of internal friction of the sand layer

If the value of $\sigma_h'$ is taken as $(K_0\sigma_v')$ , where $K_0$ is the at-rest earth pressure coefficient of the soil and $\sigma_v'$ is the vertical effective stress, and $K_0 = (1-\sin\phi)$, then equation 3.1 can be written as

$$S_u = \sigma_v' (1-\sin\phi)(\tan\phi) \qquad 3.2$$

The "equivalent cohesion" can be calculated at the middle of the sand layer, and corresponds to an average "equivalent cohesion" for the layer. For mixed soils such as sandy or silty clays, engineering judgment should be used to identify the appropriate undrained shear strength to be used in MOVEX.

## 3.4 Example factor of safety calculations

Two examples of FS calculations are provided in this section. Example 3.4.1 shows the method of determining the FS in a homogeneous, single clay layer with $S_u$ increasing with depth. Example 3.4.2 shows the method in a layered soil profile.

Example 3.4.1 is provided in Clough and Hansen (1981) as a parametric study problem in which the finite element method was used to predict the results. A cross-section of the excavation is shown in Figure 3.1, and the values of the necessary soil and support parameters are given in Table 3.1. The excavation is 12 meters wide, 17.1 meters long, and has a final depth of 15 meters. The wall is a PZ-32 sheetpile supported by crosslot bracing. The soil is assumed to be a soft to medium homogeneous clay to 30 meters. At 30 meters, a firm layer of stiff soil or rock is encountered. The calculations of FS are given in the following pages, followed by the MOVEX printout. The results of the hand calculations of FS are identical to the MOVEX calculations, which are in turn equal to the values given in Clough and Hansen (1981).

Example 3.4.2 is a case history study in Chicago provided in Smith (1986). The necessary soil and support parameters are listed in Table 3.2. This excavation is 230 feet wide, 440 feet long, and has a final depth of 29 feet. The soil is layered: layer 1 is a sand and rubble fill to 20 feet, layer 2 is a soft silty clay to 40 feet, layer 3 is a medium silty clay to 60 feet, layer 4 is a very stiff to hard silty clay to 80 feet. A firm layer of hardpan is encountered at 80 feet. The excavation is supported by a PZ-27 sheetpile wall and a combination of an upper level of tiebacks and 2 levels of rakers. A cross-section of the support system is shown in Figure 3.2. The FS calculations are given in the following pages, followed by the MOVEX printout. The answers show the same FS values.

Table 3.1

| Values used in Solving Example Problem 3.4.1 (after Clough and Hansen, 1981) |
| --- |

| Parameter | Symbol | Value |
| --- | --- | --- |
| Total Unit Weight (kPa/m) | $\gamma$ | 20 |
| Undrained Shear Strength (kPa) | $S_{u0}$ | 28.4+2.04h |
| Anisotropic Strength Ratio | $K_s$ | 1.0 |
| Wall Stiffness (kPa/m) | EI | $7.93 \times 10^4$ |
| Strut Stiffness (kPa/m) | AE/L | $1.96 \times 10^4$ |
| Number of Strut Levels | | 4 |
| Vertical Strut Spacing (m) | | 3.5 |
| Excavation Width (m) | B | 12.0 |
| Final Excavation Depth (m) | D | 15.0 |
| Excavation Length (m) | L | 17.1 |
| Depth to Firm Layer (m) | | 30.0 |
| Unit Weight of Water (kPa/m) | $\gamma_w$ | 9.81 |

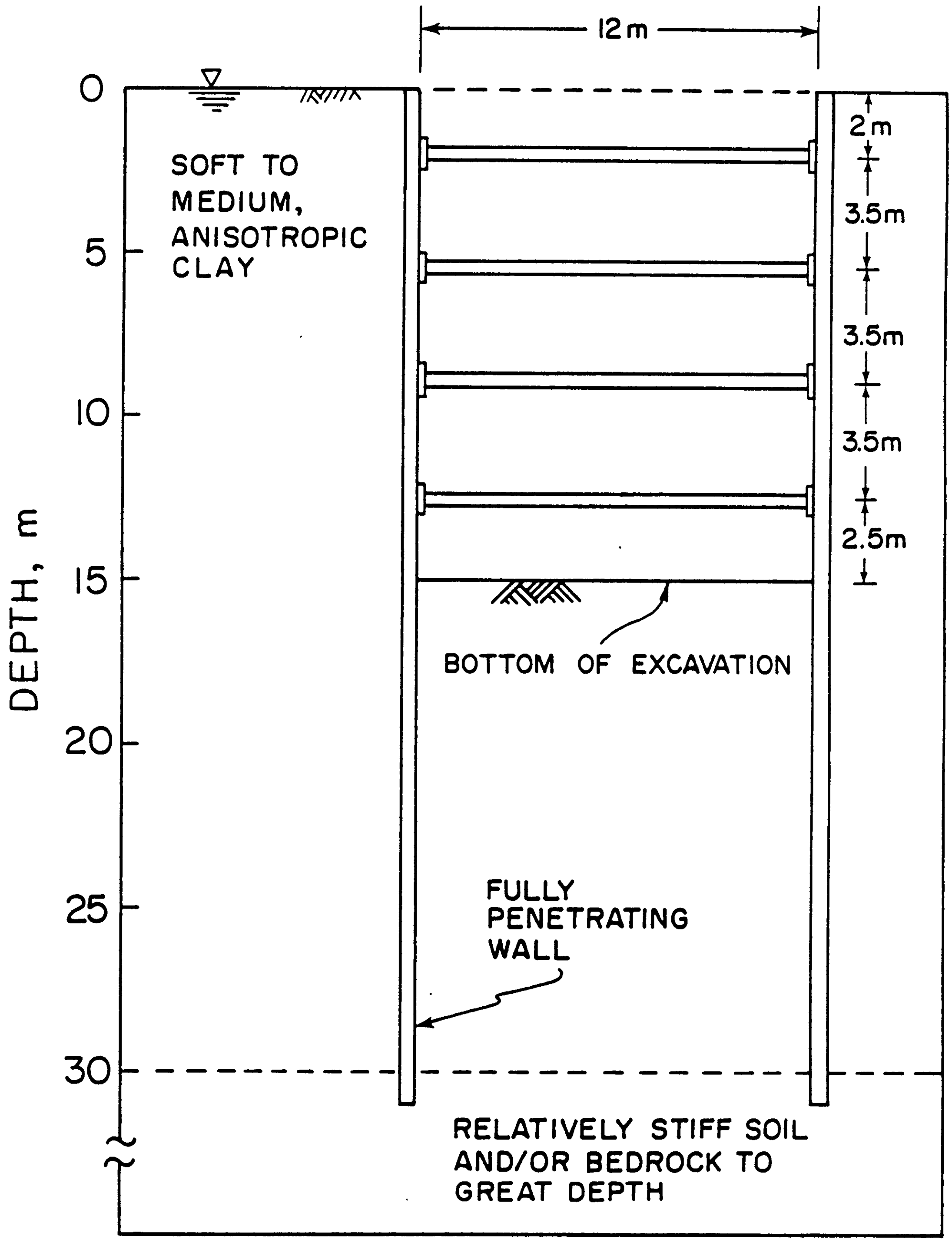



Figure 3.1 - Cross Section for Example 3.4.1
(from Clough and Hansen, 1981)

Example 3.4.1

Calculate FS at depths 9m and 15m for problem parameters listed in Table 3.1. Use the method shown in Figure 2.4.

$$FS = \frac{N_c \sum_1 (S_{ub} \cdot t)}{\sum_1 (\gamma \cdot h) T - \sum_1 (S_{us} \cdot h)}$$

For comparison with MOVEX, calculate $N_c$ by equation 2.2.

$$\begin{aligned} N_c &= 5\ (1 + 0.2\ (B/L) \\ &= 5\ (1 + 0.2\ (12/17.1)) \\ &= 5.7 \end{aligned}$$

At 9m:

Check Depth to Failure Surface:
H + 0.7B = 9 + 8.4 = 17.4m ------Governs
Depth to firm layer = 30m
T = 8.4m

$$S_{ub} = \frac{S_u(@9m) + S_u(@9+0.7B)}{2} = \frac{S_u(@9m) + S_u(@17.4m)}{2}$$

$S_u(@9m) = 28.4 + 2.04(9) = 46.8$ kPa

$S_u(@17.4m) = 28.4 + 2.04(17.4) = 63.9$ kPa

$S_{ub} = (46.8 + 63.9)/2 = 55.5$ kPa

$$\begin{aligned} S_{us} &= S_u(@4.5m) \\ &= 28.4 + 2.04(4.5) \\ &= 37.6 \text{ kPa} \end{aligned}$$

$$FS = \frac{5.7\ (55.5 \times 8.4)}{(20 \times 9)(8.4) - (37.6 \times 9)}$$

FS = <u>2.26</u>

This value compares with the value calculated by MOVEX at excavation stage 3 (see printout following this example).

At 15m:

Depth to failure surface is still controlled by 0.7B + H
T = 15 + 8.4 = 23.4

$$S_{ub} = [S_u(@15m) + S_u(@15 + 0.7B)]/2$$
$$= [S_u(@15m) + S_u(@23.4)]/2$$

$$S_u(@15m) = 28.4 + 2.04(15) = 59 \text{ kPa}$$

$$S_u(@23.4m) = 28.4 + 2.04(23.4) = 76.1 \text{ kPa}$$

$$S_{ub} = (59 + 76.1)/2 = 67.6 \text{ kPa}$$

$$S_{us} = S_u(@7.5m)$$
$$= 28.4 + 2.04(7.5)$$
$$= 43.7 \text{ kPa}$$

$$FS = \frac{5.7\ (67.6 \times 8.4)}{(20 \times 15)(8.4) - (44 \times 15)}$$

$$FS = \underline{\underline{1.74}}$$

This value compares with the value calculated by MOVEX at excavation stage 5 (see printout following this example).

PROGRAM MOVEX

Example Problem 3.4.1

The system of units used is SI
The units of length are - Meters
The units of stress are - kPA

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 1 |
| Number of struts | 4 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

No Cantilever Movements are Anticipated

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 30.00 | Cohesion | 28.40 |
| Unit Weight | 20.00 | Coh. Increase | 2.04 |

Depth to firm layer from ground surface 30.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 12.00 |
| Total length of excavation | 17.10 |
| Final depth of excavation | 15.00 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .793E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 2.00 | .1960E+05 |
| 2 | 5.50 | .1960E+05 |
| 3 | 9.00 | .1960E+05 |
| 4 | 12.50 | .1960E+05 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 3.25 |
| Nondimensional System Stiffness = | 72.46 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 2.000 |
| Factor of safety against basal heave is | 7.1436 |
| Minimum factor of safety between stages is | 7.1436 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .006 |
| Overall Maximum Lateral Wall Movement is | .006 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 5.500 |
| Factor of safety against basal heave is | 3.1304 |
| Minimum factor of safety between stages is | 3.1304 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.33 |
| Alpha S = | .83 |
| Lateral Wall Movement at this Stage is | .015 |
| Overall Maximum Lateral Wall Movement is | .015 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 9.000 |
| Factor of safety against basal heave is | 2.2564 |
| Minimum factor of safety between stages is | 2.2564 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.12 |
| Alpha S = | .91 |
| Lateral Wall Movement at this Stage is | .036 |
| Overall Maximum Lateral Wall Movement is | .036 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 12.500 |
| Factor of safety against basal heave is | 1.8857 |
| Minimum factor of safety between stages is | 1.8857 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.03 |
| Alpha S = | .96 |
| Lateral Wall Movement at this Stage is | .064 |
| Overall Maximum Lateral Wall Movement is | .064 |

Excavation stage 5

| | |
|---|---|
| Height of excavation is | 15.000 |
| Factor of safety against basal heave is | 1.7345 |
| Minimum factor of safety between stages is | 1.7345 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.00 |
| Alpha S = | 1.00 |
| Lateral Wall Movement at this Stage is | .090 |
| Overall Maximum Lateral Wall Movement is | .090 |

Table 3.2

Values used in Solving Example Problem 3.4.2

| Parameter | Symbol | Value |
|---|---|---|
| Soil Layer 1 (0-20 ft.) | | |
| Total Unit Weight (pcf) | $\gamma$ | 110 |
| Undrained Shear Strength (psf) | $S_u$ | 0 |
| Soil Layer 2 (20-40 ft.) | | |
| Total Unit Weight (pcf) | $\gamma$ | 125 |
| Undrained Shear Strength (psf) | $S_u$ | 600 |
| Soil Layer 3 (40-60 ft.) | | |
| Total Unit Weight (pcf) | $\gamma$ | 125 |
| Undrained Shear Strength (psf) | $S_u$ | 700 |
| Soil Layer 4 (60-80 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 125 |
| Undrained Shear Strength (psf) | $S_u$ | 1500 |
| Wall Stiffness (psf/ft) | EI | $3.8 \times 10^7$ |
| Strut Stiffness (psf/ft) | | |
| Strut 1 (at 4 ft) | AE/L | 508 |
| Strut 2 (at 12 ft) | AE/L | $1.11 \times 10^6$ |
| Strut 3 (at 24 ft) | AE/L | $1.59 \times 10^6$ |
| Excavation Width (ft) | B | 230 |
| Excavation Length (ft) | L | 440 |
| Final Excavation Depth (ft) | D | 29 |
| Depth to Firm Layer (ft) | $\gamma_w$ | 80 |
| Surcharge Next to Excavation (psf) | q | 650 |

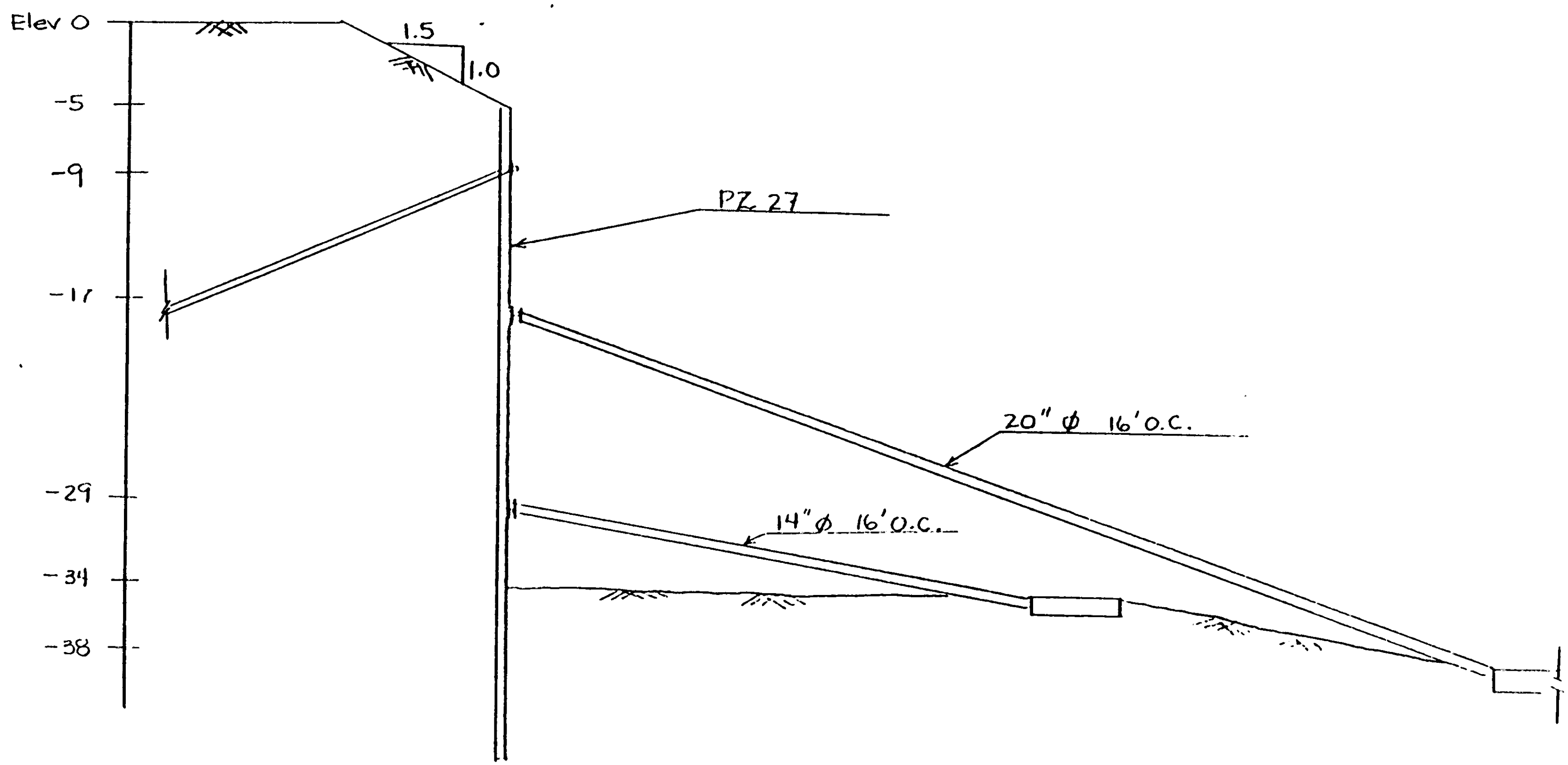



Figure 3.2 - Cross Section for Example 3.4.2
(from Smith, 1986)

Example 3.4.2

Calculate FS at depth 29 feet for problem parameters listed in Table 3.2. Use the method shown in Figure 2.4.

$$FS = \frac{N_c \sum_1 (S_{ub} \cdot t)}{\sum_1 (\gamma \cdot h) T - \sum_1 (S_{us} \cdot h)}$$

Calculate $N_c$ by equation 2.2.

$$N_c = 5\ (1 + 0.2\ (B/L)$$
$$= 5\ (1 + 0.2\ (230/440))$$
$$= 5.52$$

Check depth to failure surface:
H + 0.7B = 29 + 161 = 190 ft.
Depth to firm layer = 80 ft. ------Governs
T = 80 - 29 = 51 ft.

At 29 feet:

layer 1: $S_u = 0$, $\gamma = 110$, d = 20; $S_{us}h = 0$ $\gamma h = 2200$
layer 2: $S_u = 600$, $\gamma = 125$, h = 9; $S_{us}h = 5400$ $\gamma h = 1125$

$\sum_1 S_{us}h = 5400$ $\sum_1 \gamma h = 3325$

q = 650

Below Excavation Bottom:

layer 2: $S_{ub} = 600$ t = 11 $S_{ub}t = 6600$
layer 3: $S_{ub} = 700$ t = 20 $S_{ub}t = 14000$
layer 4: $S_{ub} = 1500$ t = 20 $S_{ub}t = 30000$

$\sum_1 S_{ub}t = 50600$

$$FS = \frac{5.52\ (50600)}{(3325 + 650)51 - 5400}$$

FS = <u>1.42</u>

This value compares with the value calculated by MOVEX at excavation stage 4 (see printout following this example).

PROGRAM MOVEX

Example Problem 3.4.2

The system of units used is English
The units of length are - Feet
The units of stress are - PSF

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 4 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

Expected Cantilever Movement at Top = .083
Anticipated Hinge Depth = 30.00

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | .00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 600.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 700.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 1500.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 80.000

WATER TABLE DATA

Unit weight of water 62.40

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 230.00 |
| Total length of excavation | 440.00 |
| Final depth of excavation | 29.00 |
| Surcharge next to excavation | 650.00 |
| Wall Stiffness (EI) | .380E+08 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 4.00 | .5080E+03 |
| 2 | 12.00 | .1110E+07 |
| 3 | 24.00 | .1590E+07 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 8.33 |
| Nondimensional System Stiffness = | 126.28 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 4.000 |
| Factor of safety against basal heave is | 3.7334 |
| Minimum factor of safety between stages is | 3.7334 |
| Average Strut Stiffness = | 508.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | 1.73 |
| Lateral Wall Movement at this Stage is | .026 |
| Cantilever Movement at this Stage is | .072 |
| Total Wall Movement at this Stage is | .098 |
| Overall Maximum Lateral Wall Movement is | .098 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 12.000 |
| Factor of safety against basal heave is | 2.3087 |
| Minimum factor of safety between stages is | 2.3087 |
| Average Strut Stiffness = | 555254.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .76 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .051 |
| Cantilever Movement at this Stage is | .050 |
| Total Wall Movement at this Stage is | .101 |
| Overall Maximum Lateral Wall Movement is | .101 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 24.000 |
| Factor of safety against basal heave is | 1.5984 |
| Minimum factor of safety between stages is | 1.5984 |

| | |
|---|---|
| Average Strut Stiffness = | 900169.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .77 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .179 |
| Cantilever Movement at this Stage is | .017 |
| Total Wall Movement at this Stage is | .196 |
| Overall Maximum Lateral Wall Movement is | .196 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 29.000 |
| Factor of safety against basal heave is | 1.4162 |
| Minimum factor of safety between stages is | 1.4162 |

| | |
|---|---|
| Average Strut Stiffness = | 906702.70 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .79 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .254 |
| Cantilever Movement at this Stage is | .003 |
| Total Wall Movement at this Stage is | .257 |
| Overall Maximum Lateral Wall Movement is | .257 |

## 3.5 Suggested method to predict wall movement and surface settlement profiles

MOVEX contains design options which can provide predictions of the maximum lateral wall movement at each excavation stage, and the vertical and lateral distribution of surface movements at each stage. The maximum lateral wall movements are calculated at each excavation stage if the design option, NOPT is set equal to zero (see MOVEX User's Guide). The program evaluates the FS and the system stiffness $(EI)/(\gamma_w h^4_{avg})$ at each stage; with these data, it "reads" the appropriate curve from Figure 2.7 to estimate the maximum lateral wall movement. If the movement distribution option, MOPT, is set equal to zero, the program also calculates the surface movements with respect to distance from the excavation at each excavation stage. The vertical distribution of surface movement is derived directly from Figure 2.10, in which the maximum value of surface settlement is assumed to be equal to the maximum lateral wall movement at that stage. Similarly, the lateral distribution of surface movements is estimated directly from Figure 2.11.

The surface settlement profile can be graphed directly from the data generated by MOVEX. The vertical and lateral movements can be used to produce movement vectors since the magnitudes and directions are known. A simpler approach is to plot only the vertical settlement at the given points, and to sketch in an assumed settlement profile. The resulting profiles can then be used to evaluate the possible effect the excavation may have on adjacent structures.

Wall movement profiles can be estimated from the maximum lateral wall movements provided by MOVEX at each excavation stage. The maximum wall movement, $\delta_M$, generally occurs just below the strut level, where the wall profile bulges out at the point of maximum movement. Since MOVEX provides the maximum movement at each stage, the final wall profile, as well as the wall profile at each excavation stage, can be estimated as illustrated in Figures 3.3 and 3.4. The method in Figures 3.3 and 3.4 assumes the strut stiffness is such that additional wall movements are prevented once the struts are installed. Note that the maximum predicted movement at the final stage actually occurs below the excavation bottom. To plot the estimated final wall profile, plot the value of $\delta_M$ predicted for each stage just below each strut level. Then sketch in the estimated wall profile. Two items must be emphasized when using MOVEX to estimate the final wall profile:

1) The estimated wall profile does not account for wall or strut yielding, strut wracking or twisting, or inadequate strut preloading. All

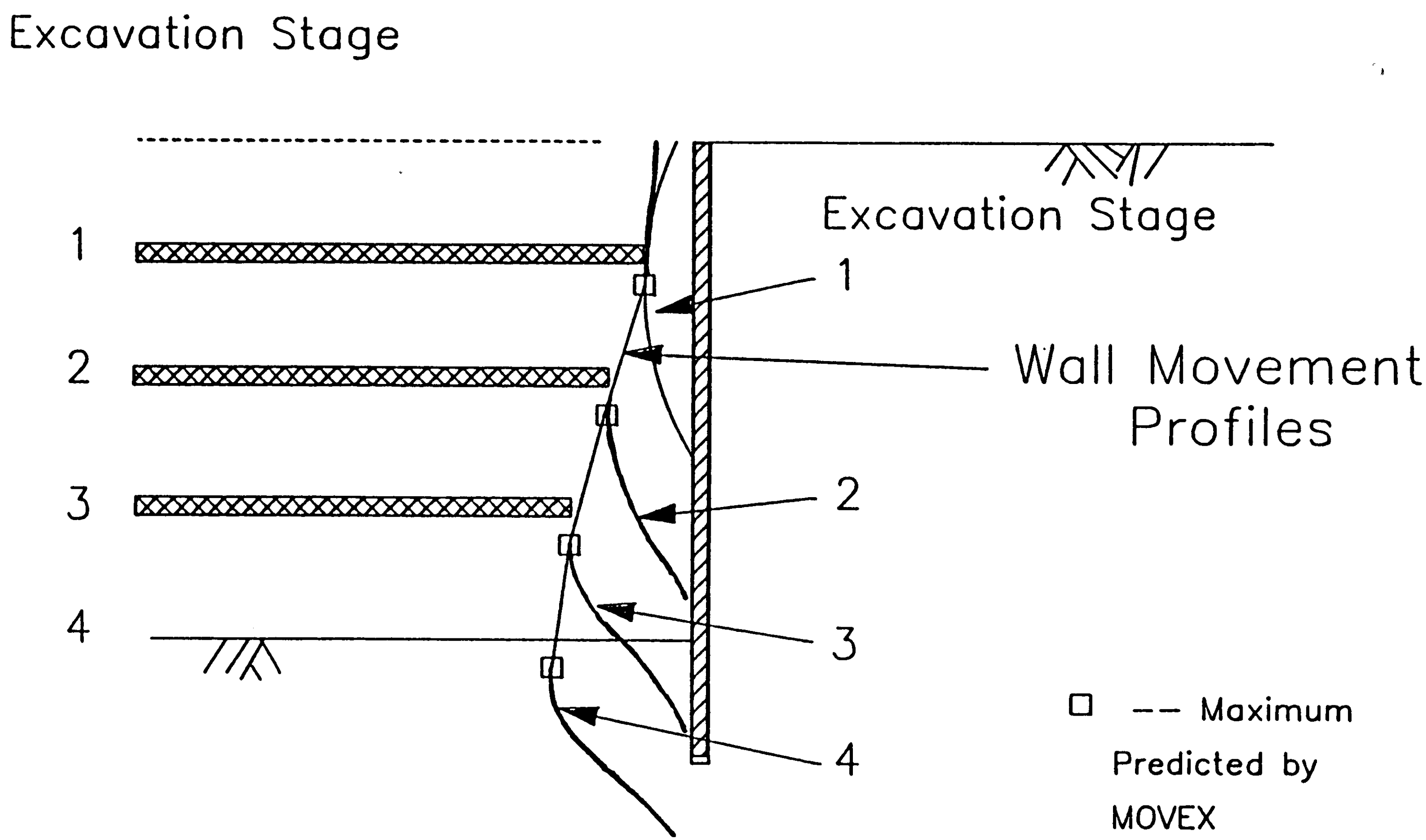



Figure 3.3 - Development of Wall Movements in Clays
Assuming High Brace Stiffness

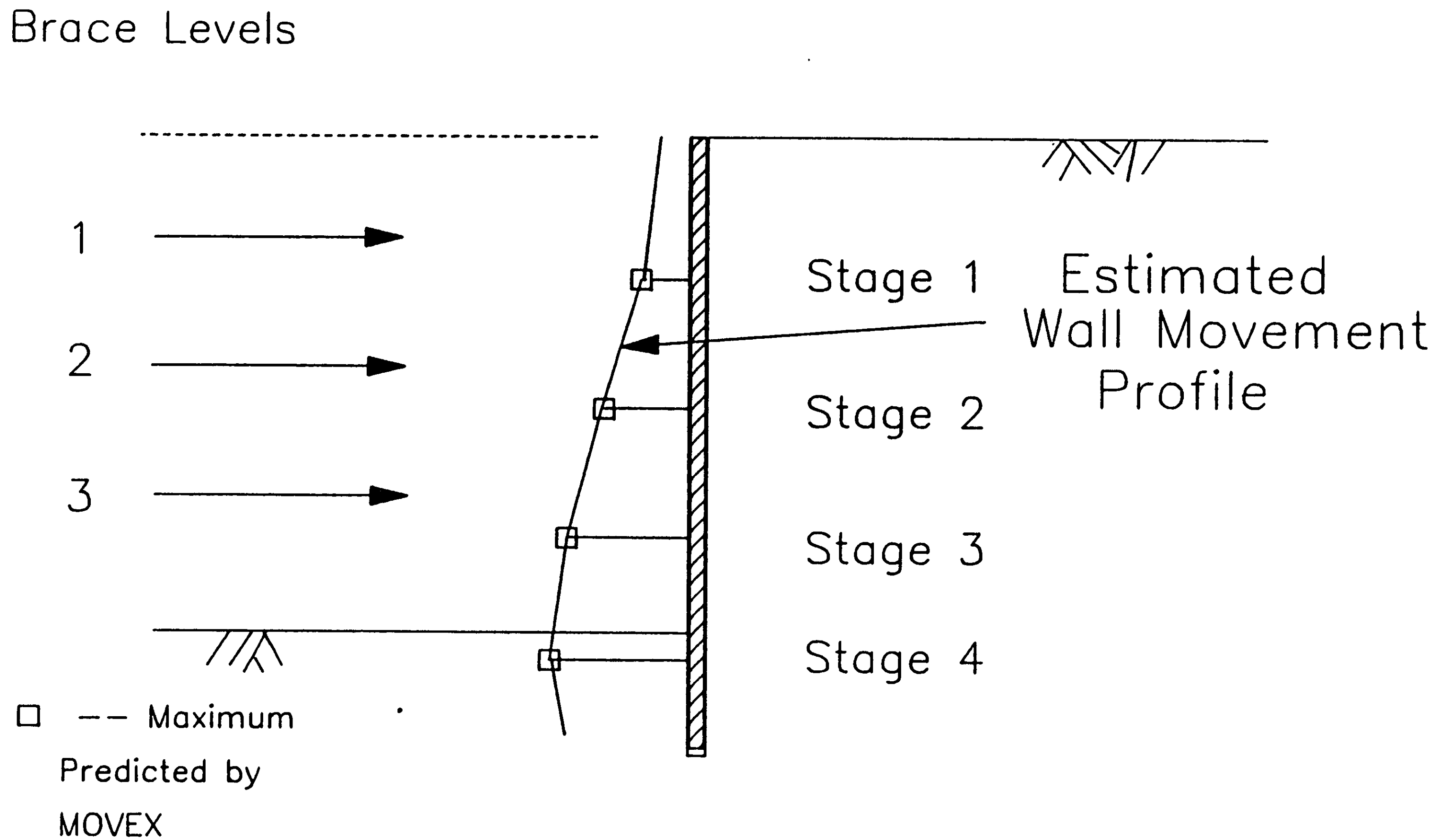



Figure 3.4

Construction of Estimated Wall Movement Profile at Final Depth using MOVEX Stage Predictions of these items can cause wall movements to exceed those predicted.

2) Cantilever wall movements must be accounted for in addition to the wall movements predicted; this can be done with the cantilever feature of MOVEX (see Chapter 5 of this thesis).

An example is provided in the following section to illustrate the method used by MOVEX to predict wall and soil movements, and the method of plotting the final wall and surface movement profiles.

## 3.6 Example wall movement and surface settlement computation

This example is a continuation of the Clough and Hansen (1981) parametric study problem used for Example 3.4.1, in which the finite element method was used to predict lateral wall movements and surface settlements. Because MOVEX is based on a combination of field data and finite element analyses, it is useful to compare the results published in the paper with the values obtained using MOVEX. The excavation cross-section is shown in Figure 3.1, and the necessary soil, wall, and excavation data are presented in Table 3.1. In the hand calculation, the lateral wall movements are determined at excavation depths of 9m and 15m. The lateral and vertical soil movements are calculated at excavation stage 5 at a distance of 15m from the wall. These values are compared to those calculated by MOVEX. Finally, a plot of the estimated wall profiles at 9m and 15m is given, along with the estimated settlements at these depths, are given in Figure 3.5. Also on the plot are the results from the finite element analyses in Clough and Hansen (1981) for this problem. The MOVEX predicted lateral wall movements are very close to the results of the finite element study. The surface settlement curves are larger than the finite element results due to the fact that the finite element analysis includes an interface friction between the soil and the wall. The interface friction restrains the settlements and keeps them less than the lateral wall movements. However, in the MOVEX predictions, the vertical settlement is assumed to be equal to the maximum lateral wall movement, based on averaging of field data trends.

Example 3.6

Estimate Maximum Lateral Wall Movement ($\delta_M$):

$$\text{System Stiffness} = \frac{EI}{(\gamma_w h^4_{avg})} = \frac{7.93 \times 10^4}{(9.81)(3.5)^4} = 54$$

At 9m:

(d = 9m)
FS = 2.3 (from Example 3.4.1)
from Figure 2.7,

$$\delta_M/d = 0.4\%$$

$$\delta_M = 0.004(9) = \underline{\underline{0.036m}}$$

At 15m:

(d = 15m)
FS = 1.7 (from Example 3.4.1)
from Figure 2.7,

$$\delta_M/d = 0.6\%$$

$$\delta_M = 0.006(15) = \underline{\underline{0.090m}}$$

MOVEX calculates $\delta_M$(9m) = 0.036m and $\delta_M$(15m) = 0.090m. Any variation which may have resulted would have been the difference between estimating a curve's position by eye, and calculating curve fitting and linear interpolation routines with MOVEX.

Estimate $\delta_V$ and $\delta_{LS}$ at stage 5, 15m from the excavation.

$\underline{\delta_V}$

FS = 1.7
= 0.090m

From Figure 2.10,

at distance/depth = 15/15 = 1.0

$\delta_V / \delta_{VM}$ = 0.975, and $\delta_{VM} = \delta_M$ = 0.090m

such that $\delta_V$ = 0.090(0.975) = $\underline{\underline{0.088m}}$

$\delta_{LS}$

From Figure 2.11,

$$\delta_{LS}/\delta_{M} = 0.5$$

$$\delta_{LS} = 0.5(0.090) = \underline{0.045m}$$

From the following printout, MOVEX gives $\delta_V$ = 0.0896m and $\delta_{LS}$ = 0.0461m. These values compare well with the hand calculations.

PROGRAM MOVEX

Example Problem 3.6

| | |
|---|---|
| The system of units used is | SI |
| The units of length are - | Meters |
| The units of stress are - | kPa |

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 1 |
| Number of struts | 4 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

No Cantilever Movements are Anticipated

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 30.00 | Cohesion | 28.40 |
| Unit Weight | 20.00 | Coh. Increase | 2.04 |

Depth to firm layer from ground surface 30.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 12.00 |
| Total length of excavation | 17.10 |
| Final depth of excavation | 15.00 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .793E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 2.00 | .1960E+05 |
| 2 | 5.50 | .1960E+05 |
| 3 | 9.00 | .1960E+05 |
| 4 | 12.50 | .1960E+05 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 3.25 |
| Nondimensional System Stiffness = | 72.46 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 2.000 |
| Factor of safety against basal heave is | 7.1436 |
| Minimum factor of safety between stages is | 7.1436 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .006 |
| Overall Maximum Lateral Wall Movement is | .006 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0063 | .0023 |
| 1.00 | .0063 | .0045 |
| 2.00 | .0060 | .0058 |
| 3.00 | .0047 | .0062 |
| 4.00 | .0038 | .0059 |
| 5.00 | .0028 | .0052 |
| 6.00 | .0019 | .0041 |
| 7.00 | .0016 | .0031 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 5.500 |
| Factor of safety against basal heave is | 3.1304 |
| Minimum factor of safety between stages is | 3.1304 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.33 |
| Alpha S = | .83 |
| Lateral Wall Movement at this Stage is | .015 |
| Overall Maximum Lateral Wall Movement is | .015 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0151 | .0054 |
| 2.75 | .0151 | .0109 |
| 5.50 | .0143 | .0139 |
| 8.25 | .0113 | .0148 |
| 11.00 | .0090 | .0142 |
| 13.75 | .0068 | .0124 |
| 16.50 | .0045 | .0098 |
| 19.25 | .0038 | .0075 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 9.000 |
| Factor of safety against basal heave is | 2.2564 |
| Minimum factor of safety between stages is | 2.2564 |

| | |
|---|---|
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.12 |
| Alpha S = | .91 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .036 |
| Overall Maximum Lateral Wall Movement is | .036 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0359 | .0088 |
| 4.50 | .0359 | .0189 |
| 9.00 | .0341 | .0276 |
| 13.50 | .0270 | .0301 |
| 18.00 | .0216 | .0250 |
| 22.50 | .0162 | .0197 |
| 27.00 | .0108 | .0156 |
| 31.50 | .0090 | .0118 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 12.500 |
| Factor of safety against basal heave is | 1.8857 |
| Minimum factor of safety between stages is | 1.8857 |

| | |
|---|---|
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.03 |
| Alpha S = | .96 |

Lateral Wall Movement at this Stage is .064
Overall Maximum Lateral Wall Movement is .064

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0636 | .0107 |
| 6.25 | .0636 | .0242 |
| 12.50 | .0605 | .0368 |
| 18.75 | .0477 | .0356 |
| 25.00 | .0382 | .0270 |
| 31.25 | .0286 | .0192 |
| 37.50 | .0191 | .0139 |
| 43.75 | .0159 | .0093 |

Excavation stage 5

Height of excavation is 15.000
Factor of safety against basal heave is 1.7345
Minimum factor of safety between stages is 1.7345

Average Strut Stiffness = 19600.00
Alpha D = 1.00
Alpha B = 1.00
Alpha S = 1.00

Lateral Wall Movement at this Stage is .090
Overall Maximum Lateral Wall Movement is .090

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0896 | .0138 |
| 7.50 | .0896 | .0312 |
| 15.00 | .0852 | .0461 |
| 22.50 | .0672 | .0407 |
| 30.00 | .0538 | .0304 |
| 37.50 | .0403 | .0211 |
| 45.00 | .0269 | .0138 |
| 52.50 | .0224 | .0083 |

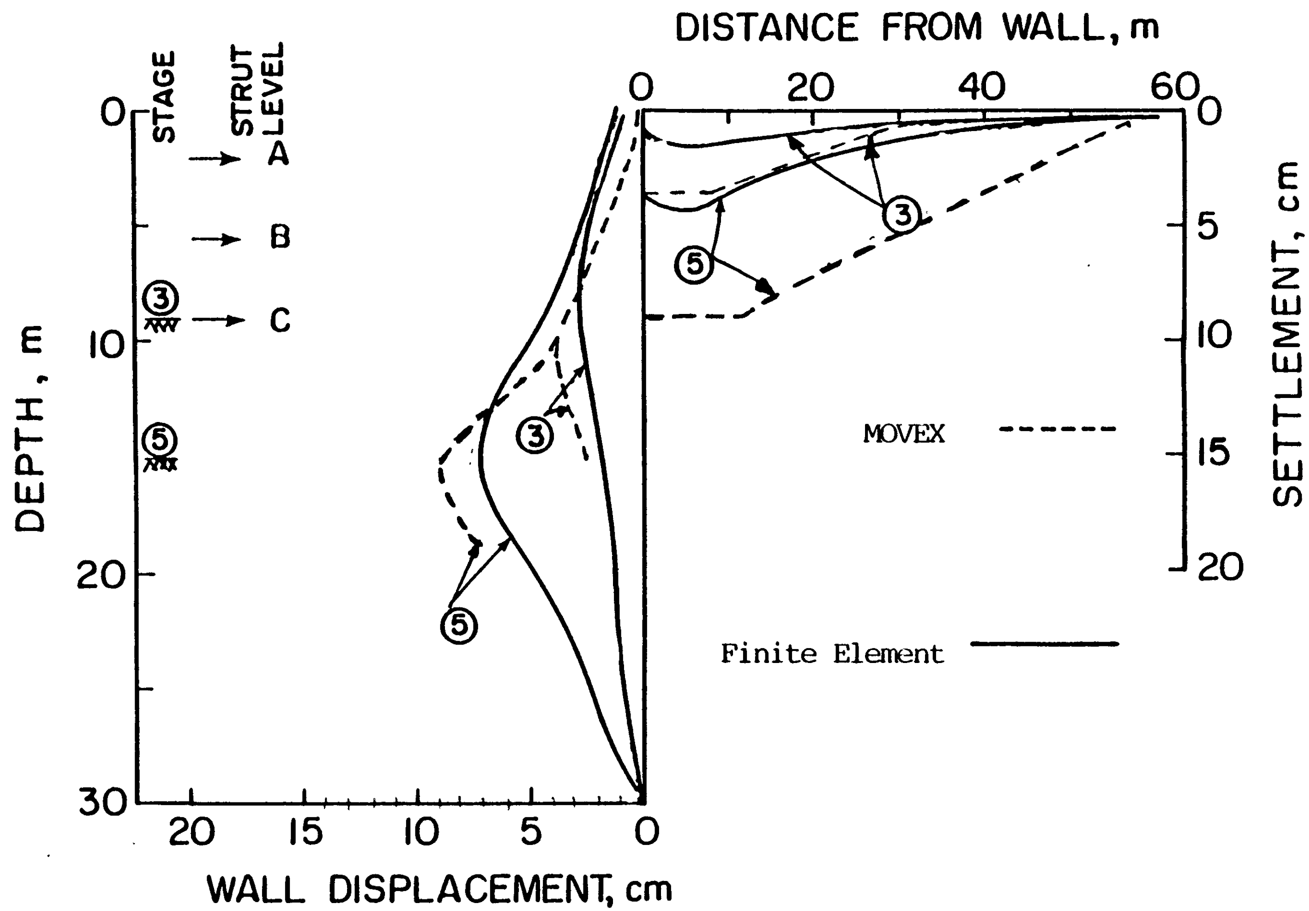



Figure 3.5 - Wall Movements and Surface Settlements for Example 3.6 MOVEX Predictions versus Finite Element Predictions (after Clough and Hansen, 1981)

# Chapter 4

# Anisotropy

## 4.1 Introduction

This chapter presents information on braced wall behavior in anisotropic soils. A background of anisotropic behavior of clays is presented, followed by a discussion of the basis with which anisotropy is incorporated into the design of supported excavations in clay. A brief discussion is provided of the method with which MOVEX accounts for soil anisotropy, and finally, a parametric study problem is presented to show the actual calculation procedure and the expected results.

## 4.2 Anisotropic behavior of clays

Hvorslev (1960) first proposed that the strength of anisotropic soils may vary with loading direction, and suggested that further research be done to evaluate this concept. Since that time, research has shown the undrained strength behavior of most clays to be directionally dependent and a function of the applied stress path. In Figure 4.1, test data for the undrained strength of four Norwegian clays shows the undrained strength to be a maximum when the soil is loaded vertically ($\beta = 0°$). This condition is that followed in conventional compression tests. The undrained strength decreases as the major

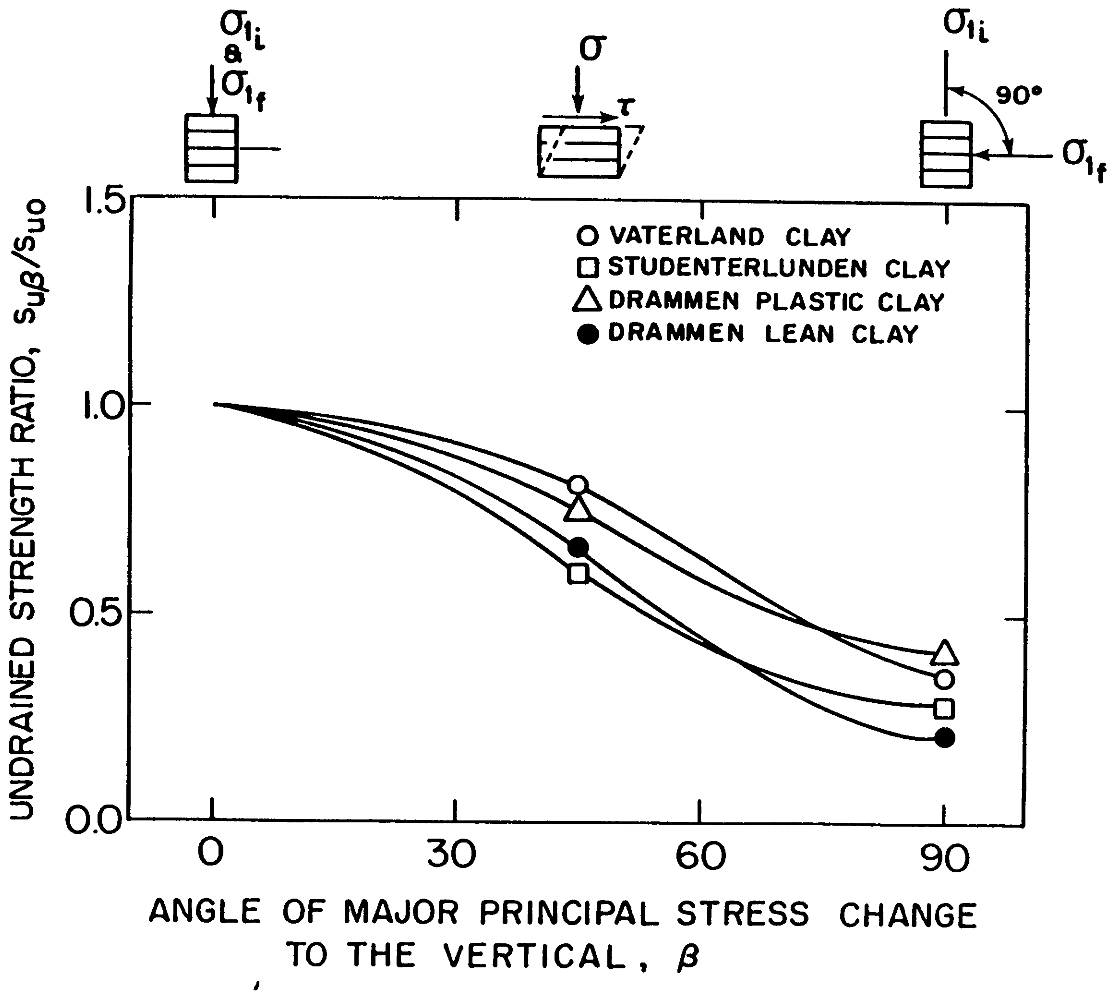



Figure 4.1 - Variation of Undrained Shear Strength with Applied Stress Path (from Clough and Hansen, 1981)

principal stresses rotate during loading from vertical ($\beta$ >0°). If the principal stresses rotate as much as 90°, the data for the Norwegian clays show $S_{U0}/S_{U90}$ ranging from 0.2 to 0.4. These values suggest that the actual soil strength may be as low as 25% of the typically predicted soil strength in cases where the loading rotates the principal stresses from the vertical to the horizontal direction.

Duncan (1965), and Ladd and his co-workers (1974, 1977), and Jamiolkowski et al. (1985) have presented databases for the anisotropic variation of the undrained strength of a variety of clays. This information suggests that anisotropy is strongest in clays with low plasticity, like the Norwegian clays illustrated in Figure 4.1 Hansen and Clough (1980) have also documented data on the modulus variation of clays for undrained conditions. The modulus anisotropy effect can also be strong for low plasticity clays.

The reason for concern over the issue of undrained anisotropy of clays for supported excavations lies in the manner in which the principal stresses in the soils adjacent to the excavation rotate during soil removal. In Figure 4.2, the pattern for principal stress rotation during excavation in front of a cantilevered wall is shown. On the active side of the wall where the soil is not excavated, the direction of the principal stresses remains unchanged during the loading process, i.e., there is no

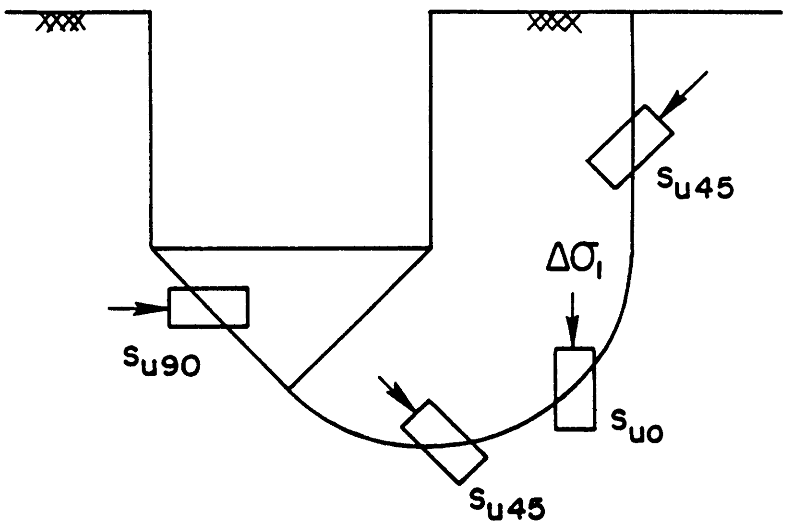



Figure 4.2 - Rotation of Principal Stresses
during Excavation (from Clough and Hansen, 1981)

rotation, and the conditions correspond to those in the conventional compression loading test. On the excavation side of the wall, the principal stresses in the passive zone of the soil rotate 90 degrees during excavation. This results because the horizontal stress, which initially is the minor principal stress, becomes the major principal stress after excavation. Thus, the undrained strength and modulus of the soil in the passive zone will not be that as determined in a conventional compression test. In particular, it will be somewhat less than that from the conventional test. Assuming that the conventional test is done carefully so as to determine the correct compressive strength, the use of the compression test strength to characterize both the active and passive zone strength is an unconservative process.

Given the previous information, it is reasonable to expect that design engineers should consider anisotropy in their analyses of the stability of supported excavations. However, this is not often done because of a lack of test data, or because of a perceived inconvenience to the design process. Clough and Hansen (1981) recognized this problem, and attempted to formulate guidelines to simplify the accomodation of the principles of anisotropic behavior. First, they noted that the anisotropy is not always a significant factor in the behavior of excavations. It is most important where the soil can be shown to be strongly anisotropic, or where the FS is close to one. Second, they established a means to easily incorporate anisotropic strength variations into the basal heave analysis. Finally, they developed finite element techniques which included anisotropy for clays, and determined the influence of clay anisotropy on the deformations predicted for supported excavations in undrained clays. Their results allow for incorporation of the effects of anisotropy into the program MOVEX.

## 4.3 The basis for incorporation of clay anisotropy into the analysis of supported excavations in clay

The first aspect of this problem is to be able to calculate the true FS, including anisotropy. Clough and Hansen (1981) did this by incorporating a solution for bearing capacity analysis by Davis and Christian (1971) into Terzaghi's basal heave analysis. Using the trends of undrained shear strength with the angle of stress rotation from vertical, $\beta$ , Davis and Christian (1971) developed an anisotropic bearing capacity factor, $N_c^*$, to account for soil anisotropy. This factor can be applied directly to the FS calculation for excavations, where the bearing capacity factor denoted $N_c$ is replaced with $N_c^*$ times $S_{u0}$.

The FS equation for anisotropic soils is then

$$FS = \frac{1}{H} \; \frac{N_c^* S_{u0}}{\gamma - \dfrac{S_{u45}}{0.7B}} \qquad (4.1)$$

where: $\gamma$ = total unit weight of the soil
H = depth of excavation
B = width of excavation
$S_{u0}$ = undrained shear strength at $\beta = 0°$
$S_{u45}$ = undrained shear strength at $\beta = 45°$

Because of laboratory and field testing constraints, it is more convenient to express soil strength in terms of $S_{u0}$ and $S_{u90}$. To this end, a term $K_s$, defined as $S_{u90}/S_{u0}$, is used in the FS equation:

$$FS = \frac{1}{H} \; \frac{N_c^* S_{u0}}{\gamma - \dfrac{0.5 S_{u0}(1+K_s)}{0.7B}} \qquad (4.2)$$

If the failure mechanism is expected to be influenced by an underlying rigid base, equations 4.1 and 4.2 can be modified by substituting D for 0.7B (see Figure 2.1). The term $N_c^*$ is a function of $K_s$, and typical values are given in Table 1 of Davis and Christian (1971). $K_s$ can be determined directly from laboratory tests on the soil in question, or can be estimated from the data shown in Figure 4.3 as adapted from Hansen and Clough (1980) and Jamiolkowski, et al (1985).

Clough and Hansen (1981) developed the curve shown in Figure 4.4 to allow a direct modification of the isotropic FS using only the anisotropic strength ratio, $K_s$. The

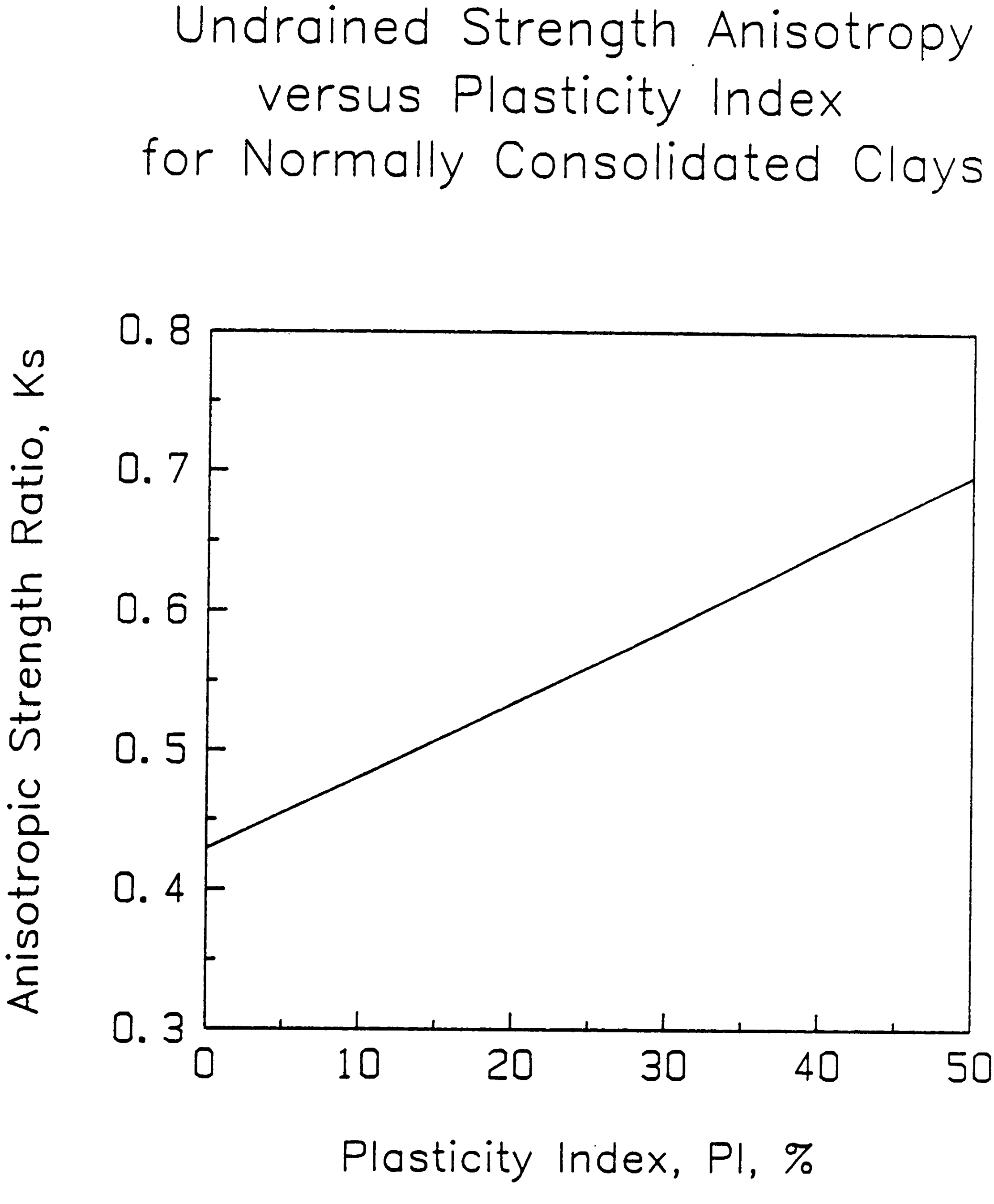



Figure 4.3 - Anisotropic Strength Ratio versus Plasticity Index (adapted from Hansen and Clough, 1980 and Jamiolkowski, et al, 1985)

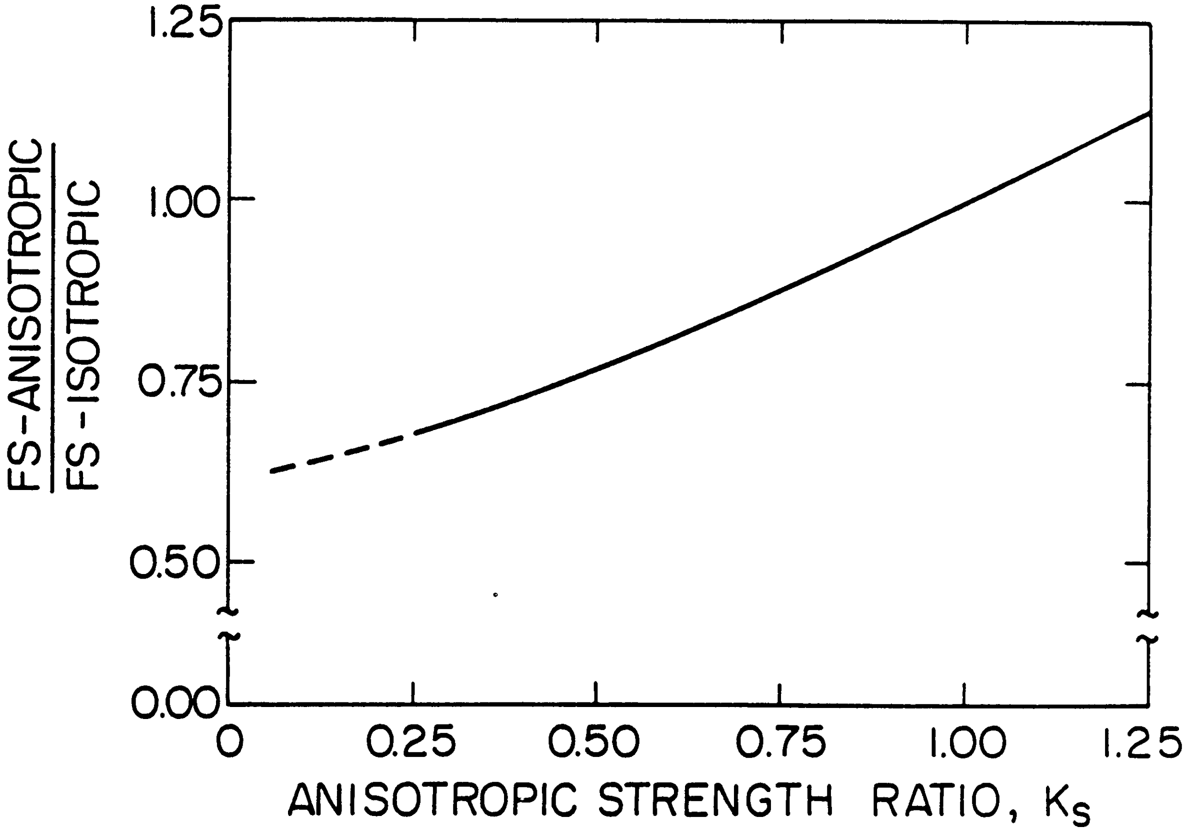



Figure 4.4 - Factor of Safety versus Anisotropic Strength Ratio (from Clough and Hansen, 1981)

reader is referred to the original paper for the full development of the curve in Figure 4.4. The underlying assumptions are:

1) no underlying rigid base to influence the failure mechanism,
2) excavation width is greater than 15m (50 ft.), and
3) $K_s$ is 0.25 or greater.

As can be noted from Figure 4.4, the FS for strongly anisotropic soils can be significantly lower than the FS as conventionally calculated for isotropic soils.

Clough and Hansen (1981) show that maximum lateral wall movements are increased in the presence of anisotropic soils as compared to isotropic soils, and that the difference between the movements increases as $K_s$ decreases, and as the FS decreases. They also show that as long as the FS is modified to include anisotropy, the actual wall behavior exhibited in isotropic and anisotropic soils show the same wall displacement and surface settlement trends.

## 4.4 How MOVEX accounts for anisotropy

MOVEX accounts for anisotropy using Figure 4.4, described in the preceding section. The user enters a value of the anisotropic strength ratio for the soil, $K_s$, in the data file. MOVEX takes this value (labeled "xks" in the program) and reads the corresponding value of (FS-anisotropic/FS-isotropic) from Figure 4.4. For simplicity, the ratio (FS-anisotropic/FS-isotropic) is labeled "alpha k", or "ak", in the program. The value of "ak" is then applied in the FS equation,

$$FS = \frac{N_c \sum (S_{ub} \cdot t)}{[\sum (\gamma \cdot h) + q]\, T - \sum (S_{us} \cdot h)} \, (ak) \qquad (4.1)$$

where all of the terms are defined in Figure 2.4. Note that the values of $S_{ub}$ and $S_{us}$ are average values when the shear strength increases within the layer. Because of the necessary rigors of programming, the FS calculation shown in the MOVEX listing does not look like equation 4.1, but is theoretically the same equation.

4.5 Example Problem

The example provided is that described in Clough and Hansen (1981) as a parametric study problem in which the finite element method was used to predict results. This problem was used earlier for Example 3.4.1. A cross section of the excavation considered is given in Figure 3.1, and parameter values used in solving the problem are given in Table 3.1. The difference between this problem and the one presented in Example 3.4.1 is the anisotropic strength ratio of the soil. For this case, the value Ks is equal to 0.5. The value of "ak" can be read from Figure 4.4, and is equal to 0.75.

The basic FS calculation can be seen in Example 3.4.1, and is modified by

FS(anisotropic) = "ak" FS(isotropic)

such that at Stage 3 (9m), the FS is

FS = 0.75 x 2.26 = 1.7

and at Stage 5 (15m), the FS is

FS = 0.75 x 1.74 = 1.3

These values compare directly with those as given in Clough and Hansen (1981) and with those calculated by MOVEX shown in the following printout.

Predictions of wall movements and surface settlements from Clough and Hansen (1981) using the finite element method and those using MOVEX are shown in Figure 4.6. In the early excavation stages, the wall movements and soil settlements for both isotropic (Examples 3.4.1 and 3.6) and anisotropic (Example 4.5) cases are similar because the FS value is relatively high. In this environment, the maximum wall movements determined by MOVEX are very close to those from the finite element analyses, while the predicted settlements behind the wall from MOVEX are larger than those from the finite element analyses. The difference in the settlement predictions derives from the fact that in MOVEX, the maximum settlement is assumed to be equal to the maximum lateral wall movement. This assumption is based on field data trends. Whereas, in the finite element program, the interface friction between the wall and the soil restrains the settlements and keeps them less than the lateral wall movements.

At the full excavation depth, the isotropic and anisotropic FS values are 1.7 and 1.3, respectively, and there are clearly larger movements for the anisotropic case. The MOVEX predictions correctly anticipate the difference between the isotropic and anisotropic cases. MOVEX predictions are very close to the finite element values for lateral wall movement, but higher for the soil settlements behind the wall. The reason for this is as explained previously. For the anisotropic case, the MOVEX prediction for lateral wall movement is lower than that from the finite element program. The reason for this is due to differences in the finite element predictions for the low FS case and the field data base that is incorporated in the MOVEX program for these conditions.

PROGRAM MOVEX

Example 4.5: Clough & Hansen Parametric Study Problem
(Anisotropic Case)

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 1 |
| Number of struts | 4 |
| Design Option | 0 |
| Anisotropic Strength Ratio | .500 |

CANTILEVER EFFECT

No Cantilever Movements are Anticipated

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 30.00 | Cohesion | 28.40 |
| Unit Weight | 20.00 | Coh. Increase | 2.04 |

Depth to firm layer from ground surface 30.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 12.00 |
| Total length of excavation | 17.10 |
| Final depth of excavation | 15.00 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .793E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 2.00 | .1960E+05 |
| 2 | 5.50 | .1960E+05 |
| 3 | 9.00 | .1960E+05 |
| 4 | 12.50 | .1960E+05 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 3.25 |
| Nondimensional System Stiffness = | 72.46 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 2.000 |
| Factor of safety against basal heave is | 5.5006 |
| Minimum factor of safety between stages is | 5.5006 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .006 |
| Overall Maximum Lateral Wall Movement is | .006 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0063 | .0023 |
| 1.00 | .0063 | .0045 |
| 2.00 | .0060 | .0058 |
| 3.00 | .0047 | .0062 |
| 4.00 | .0038 | .0059 |
| 5.00 | .0028 | .0052 |
| 6.00 | .0019 | .0041 |
| 7.00 | .0016 | .0031 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 5.500 |
| Factor of safety against basal heave is | 2.4104 |
| Minimum factor of safety between stages is | 2.4104 |
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.33 |
| Alpha S = | .83 |
| Lateral Wall Movement at this Stage is | .022 |
| Overall Maximum Lateral Wall Movement is | .022 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0221 | .0080 |
| 2.75 | .0221 | .0159 |
| 5.50 | .0210 | .0203 |
| 8.25 | .0166 | .0217 |
| 11.00 | .0133 | .0208 |
| 13.75 | .0100 | .0181 |
| 16.50 | .0066 | .0144 |
| 19.25 | .0055 | .0111 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 9.000 |
| Factor of safety against basal heave is | 1.7374 |
| Minimum factor of safety between stages is | 1.7374 |

| | |
|---|---|
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.12 |
| Alpha S = | .91 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .054 |
| Overall Maximum Lateral Wall Movement is | .054 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0543 | .0083 |
| 4.50 | .0543 | .0189 |
| 9.00 | .0516 | .0280 |
| 13.50 | .0407 | .0248 |
| 18.00 | .0326 | .0185 |
| 22.50 | .0244 | .0128 |
| 27.00 | .0163 | .0085 |
| 31.50 | .0136 | .0051 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 12.500 |
| Factor of safety against basal heave is | 1.4520 |
| Minimum factor of safety between stages is | 1.4520 |

| | |
|---|---|
| Average Strut Stiffness = | 19600.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.03 |
| Alpha S = | .96 |

Lateral Wall Movement at this Stage is .095
Overall Maximum Lateral Wall Movement is .095

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0947 | .0174 |
| 6.25 | .0947 | .0380 |
| 12.50 | .0904 | .0510 |
| 18.75 | .0694 | .0425 |
| 25.00 | .0536 | .0325 |
| 31.25 | .0397 | .0226 |
| 37.50 | .0266 | .0147 |
| 43.75 | .0222 | .0083 |

Excavation stage 5

Height of excavation is 15.000
Factor of safety against basal heave is 1.3355
Minimum factor of safety between stages is 1.3355

Average Strut Stiffness = 19600.00
Alpha D = 1.00
Alpha B = 1.00
Alpha S = 1.00

Lateral Wall Movement at this Stage is .134
Overall Maximum Lateral Wall Movement is .134

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1345 | .0212 |
| 7.50 | .1345 | .0476 |
| 15.00 | .1300 | .0684 |
| 22.50 | .0931 | .0584 |
| 30.00 | .0652 | .0438 |
| 37.50 | .0461 | .0302 |
| 45.00 | .0315 | .0193 |
| 52.50 | .0265 | .0110 |

# Chapter 5

## Cantilever Wall Movements

### 5.1 Introduction

This chapter presents a theory of excavation support wall behavior for walls which exhibit initial cantilever movements. If the initial cantilever movements are specified, the proposed theory is used in MOVEX to predict lateral wall and ground surface movements. The method used by MOVEX to evaluate the cantilever effect is provided in this chapter. Suggestions are provided for applying the cantilever feature, and an example problem demonstrates its use.

### 5.2 Behavior of walls with significant cantilever movement

In the construction of braced excavations, the installation of the first level of struts is often delayed. Such delays cause the top portion of the support walls to show lateral deflection toward the excavation, and this deflection is termed cantilever movement. Walls with initial cantilever movements exhibit larger overall lateral deflections and surface settlements when compared to similar walls with no significant cantilever movements. However, when the effects of the cantilever movements are removed, the walls show movement trends similar to those of the walls with no significant cantilever movements. The cantilever effect is proposed in this thesis to be a linear amount which decreases with depth to some hinge point, at which the effect is zero. The cantilever movement is a maximum at the top of the wall, and this value is what governs the subsequent movements.

The cantilever effect is illustrated in Figure 5.1. The shaded cantilever movement is shown to decrease linearly with depth to the hinge point. The hinge point is arbitrarily chosen to define to depth at which the cantilever movement is zero, and is evaluated simply by judgement. The wall profile of Figure 5.1 can be compared with that shown in Figure 5.2, where the cantilever movements have been removed.

A striking example of the trends of similar walls with and without cantilever movements is shown in Figure 5.3. Figure 5.3 is adapted from data presented in Clough and Davidson (1977) in which two phases of a deep excavation in San Francisco soft clay (Bay Mud) were studied. The soil conditions were the same and the excavation support systems were very similar for the two phases of construction; however, the top level of strut installation was significantly delayed for the Phase II wall. Figure 5.3 shows the obvious difference in the lateral wall movements experienced by the two walls. If the movement pattern of the Phase II wall is manipulated by systematically reducing the amount of lateral movement in manner described above, the wall movement pattern becomes very similar to that exhibited by the Phase I wall. This trend is illustrated

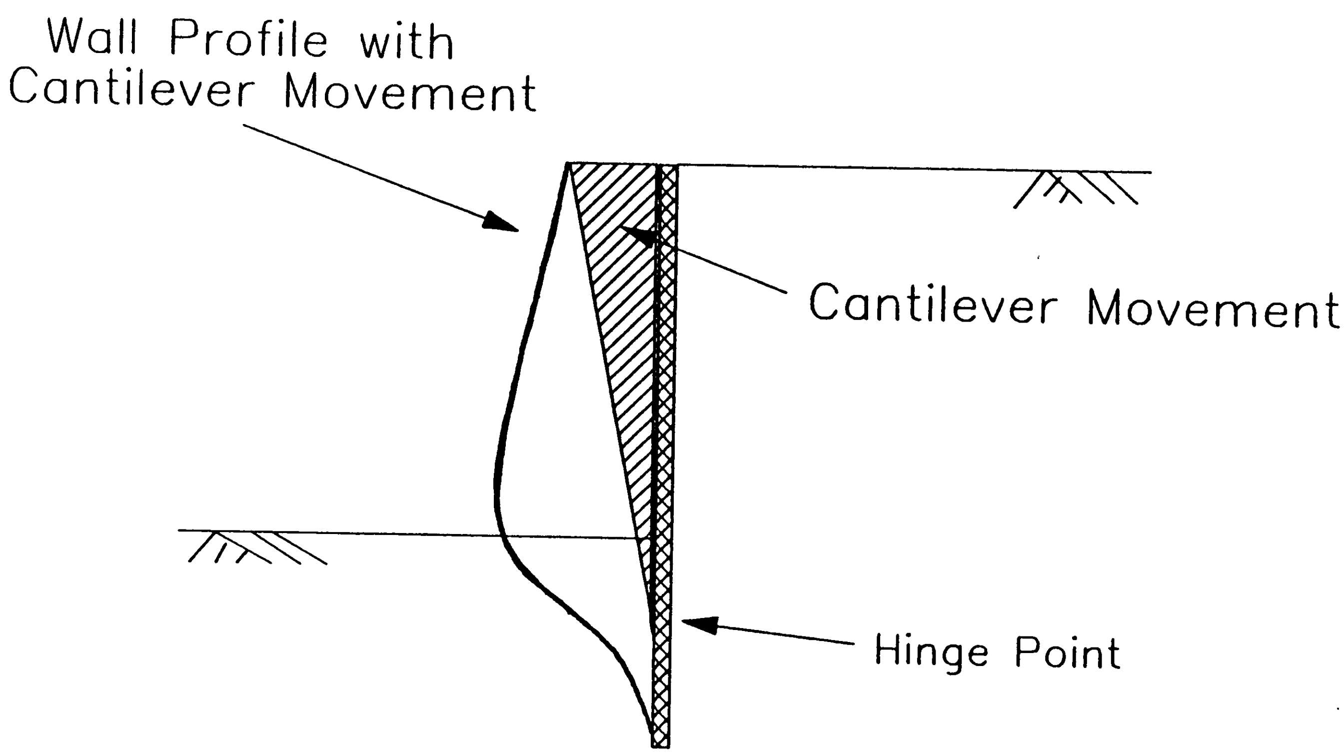



Figure 5.1

Lateral Wall Displacements with Large Initial Cantilever Movements

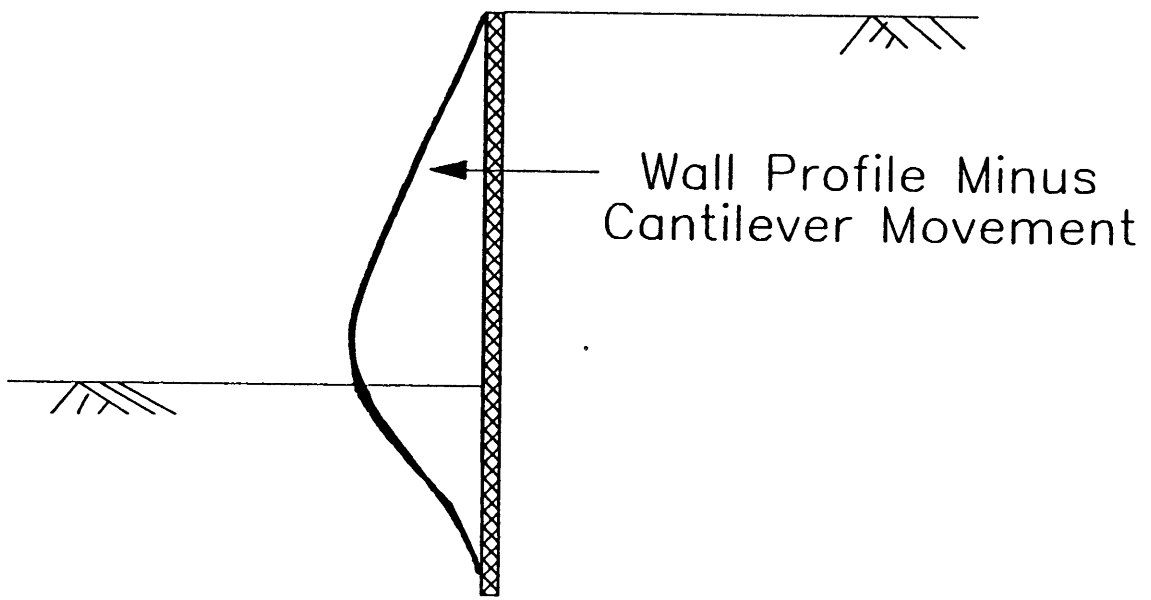



Figure 5.2
Lateral Wall Displacements minus
Initial Cantilever Movements

in Figure 5.4, in which 6cm of cantilever movement was removed from the Phase II displacements. In most actual excavations, there exists a small amount of cantilever movement even under the best conditions. Thus, in order to better compare the Phase I and Phase II walls, a cantilever effect of 6cm, rather than the entire 9cm, was removed from the Phase II profile. This same method was used in Figures 2.12 and 2.13, described in Chapter 2.

To account for cantilever movements, MOVEX uses the theory shown in Figure 5.1 in the reverse manner. First, the "normal" lateral wall movements are predicted for each strut level, neglecting cantilever effects. Then, the cantilever movement associated with each strut level is calculated. The total lateral wall movements reported by MOVEX at each strut level are then the sum of cantilever and "normal" lateral wall movements.

MOVEX reports the total maximum lateral wall displacement at each excavation stage, as well as the overall maximum wall displacement for the entire wall. As stated above, the amounts of cantilever movement and maximum lateral movement are summed to obtain the total lateral wall displacement at each stage. The overall maximum wall displacement is also reported, which is the maximum movement predicted for the wall at any stage. The value of overall maximum lateral wall displacement for the wall is used to calculate the distribution of ground

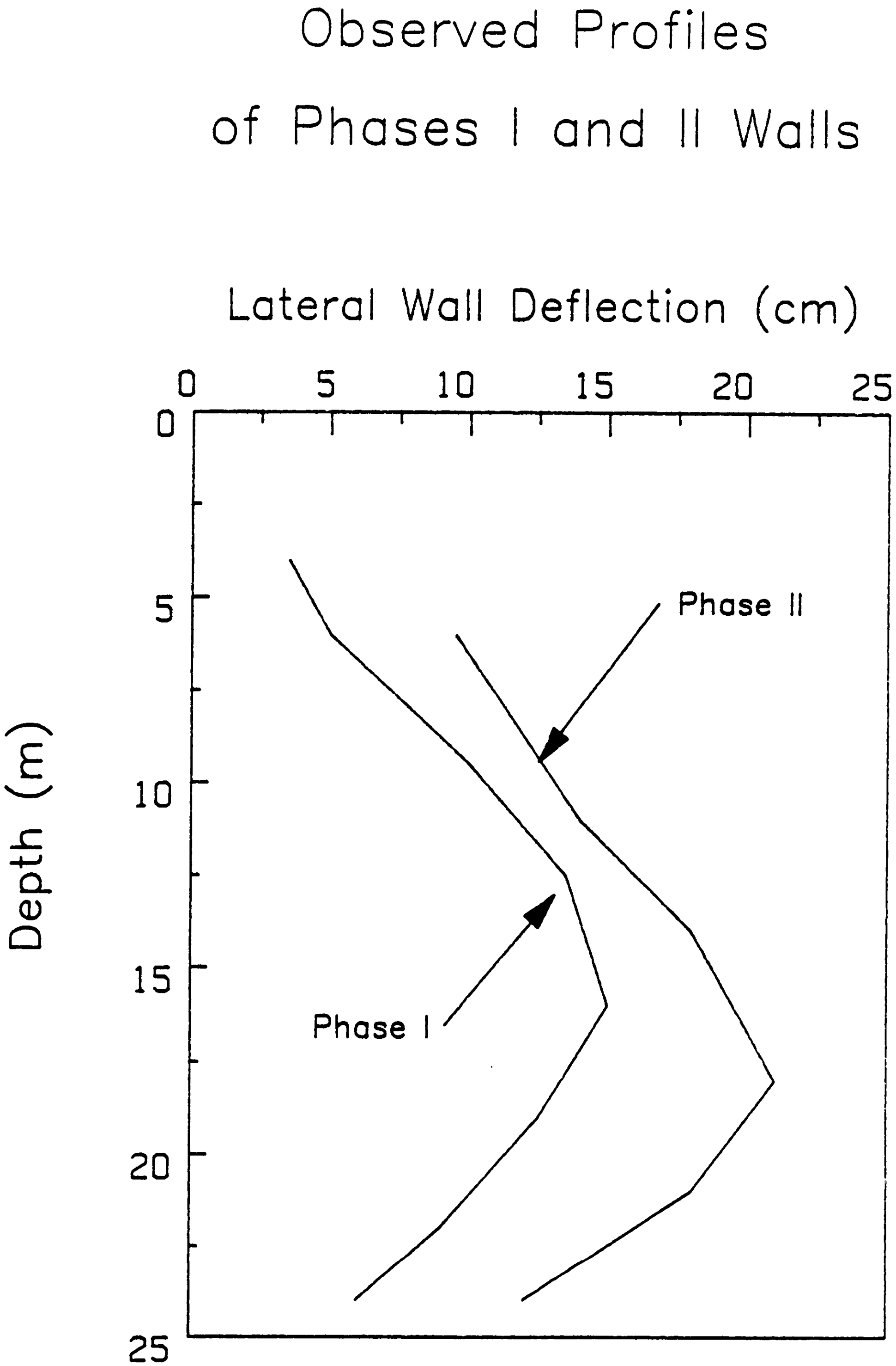



Figure 5.3 - Trends of Similar Walls with and without Cantilever Movements (after Clough and Davidson, 1977)

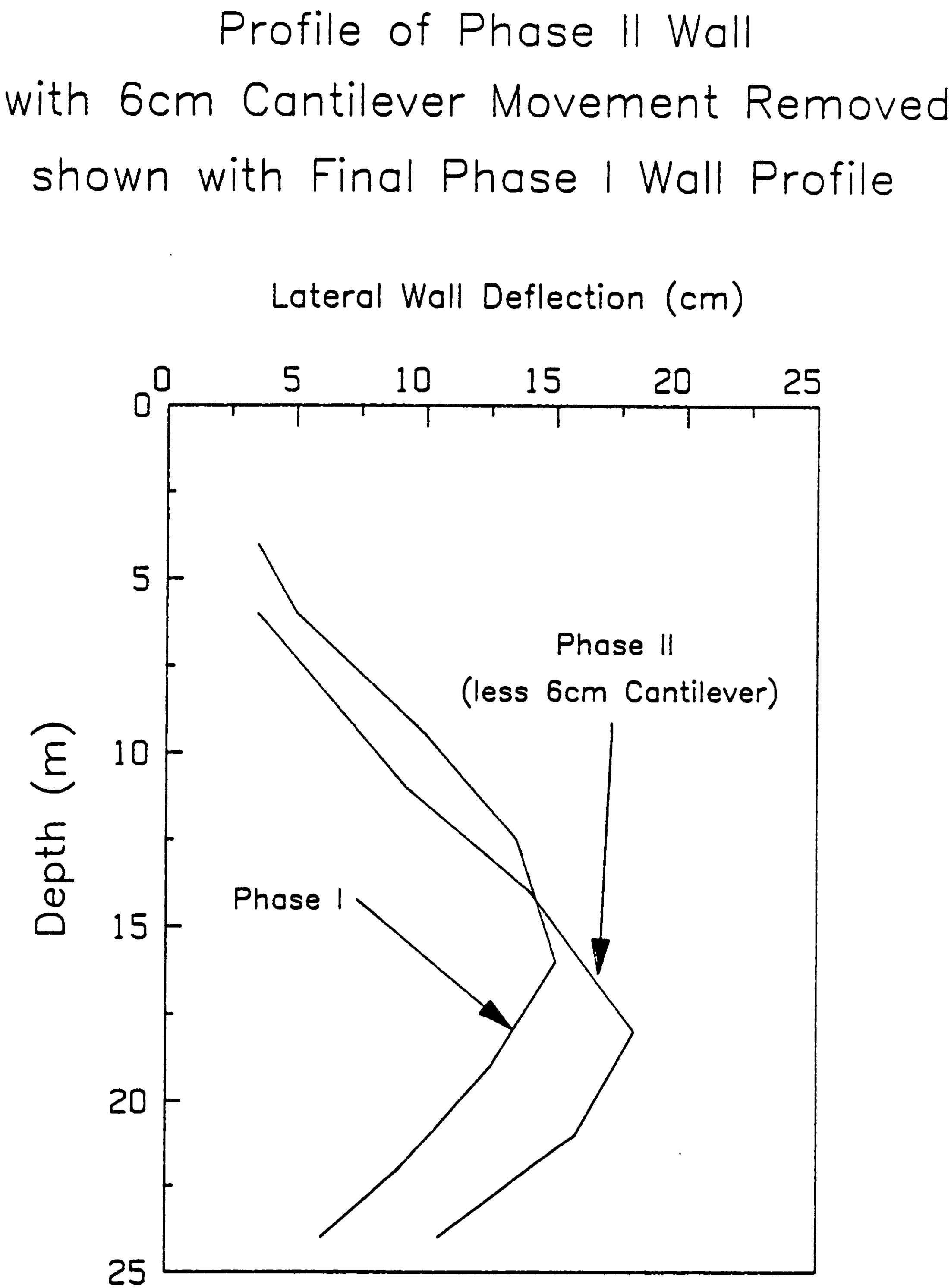



Figure 5.4 - Trends of Similar Walls Manipulated to have Equal Cantilever Wall Movements

surface movements. The reason for this is maximum wall movements govern surface displacements, which for MOVEX predictions would be the overall maximum lateral wall movement.

## 5.3 Suggested applications of the cantilever movement prediction feature

The cantilever effect is a separate design option offered by MOVEX. In order to include a cantilever movement, the cantilever effect parameter, "CE," is set equal to 1 (see MOVEX User's Guide). The values of cantilever movement at the top of the wall and the hinge depth must be specified by the user. The reported wall and surface movements will then include the effect of the cantilever movement.

The cantilever feature is useful to the designer because best and worst case movement conditions can be evaluated for a given excavation system. For example, the effects of construction delays or poor construction practices can be anticipated during the design phase. If the first strut is expected to be delayed, the designer can specify cantilever movements in MOVEX to evaluate the resulting surface settlements.

## 5.4 Example problem

The example considered here is from Clough and Davidson (1977) which was used to demonstrate the effects of cantilever movements in Figures 5.2 and 5.3. Only the

Phase II wall is considered in this example. The excavation was a deep excavation project in San Francisco soft clay. The top soil layer is a rubble fill to 7.5m, underlain by 22.5m of soft clay. Below the soft clay is a sand layer. The excavation was supported by PZ-32 sheetpiles and braces of 0.66m diameter x 0.8cm steel pipe. The excavation parameters are listed in Table 5.1. The shear strength of the sand layer given in Table 5.1 is actually an equivalent cohesion calculated assuming the sand density is 20 kPa/m and the angle of internal friction is 30 degrees.

This example was evaluated for three different conditions: first, with no cantilever effect; second, with a cantilever effect of 9.5cm at the first strut level; and third, with a cantilever effect of 3.5cm at the first strut level. The cantilever movements were varied to represent the observed 3.5cm cantilever movement of the similar Phase I wall described in section 5.2, and the 9.5cm movement of the Phase II wall. The cantilever movements for the observed wall profiles are measured at depths of about 6m. However, MOVEX computes the cantilever effect based on the movement at the top of the wall. Thus the values of cantilever at the top of the wall were used in MOVEX as 11.4cm and 4.2cm in order to properly obtain cantilever movements of 9.5cm and 3.5cm, respectively, at the depth of the first level of struts.

The results of the MOVEX analyses are presented in Figure 5.5, where the three profiles show the effect of varying the amount of cantilever movements. Figure 5.6 shows the comparison of the MOVEX results for the 9.5cm cantilever case with the observed profile of the Phase II wall. Figure 5.7 shows three walls with 3.5cm of cantilever movement: the Phase I profile, the Phase II profile minus 6cm of cantilever, and the MOVEX predicted profile for the Phase II wall with 3.5cm of cantilever. Note that Figure 5.7 is simply Figure 5.4 with the added profile of the MOVEX prediction of Phase II with 3.5cm cantilever. The MOVEX results in all of the predictions show patterns very similar to the observed movement patterns.

Table 5.1

Values used in Solving Example Problem 5.4

| Parameter | Symbol | Value |
|---|---|---|
| Rubble Fill (0-7.5m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 14.4 |
| Undrained Shear Strength (kPa) | $S_{u0}$ | 20 |
| Soft Clay (7.5-30m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 15.7 |
| Undrained Shear Strength (kPa) | $S_{u0}$ | 24.5+1.31h |
| Sand (30-45m) | | |
| Total Unit Weight (kPa/m) | | 20 |
| Angle of Internal Friction (degrees) | 0 | 30 |
| Equivalent Shear Strength (kPa) | $S_{u0}$ | 79 |
| Wall Stiffness (kPa/m) | EI | $6.01 \times 10^4$ |
| Strut Stiffness (kPa/m) | AE/L | $3.53 \times 10^5$ |
| Number of Strut Levels | | 3 |
| Vertical Strut Spacing (m) | | 5, 3, 3.5 |
| Excavation Width (m) | B | 41.25 |
| Final Excavation Depth (m) | D | 13.8 |
| Excavation Length (m) | L | 82.5 |
| Depth to Firm Layer (m) | | 100.0 |
| Unit Weight of Water (kPa/m) | $\gamma_w$ | 9.81 |

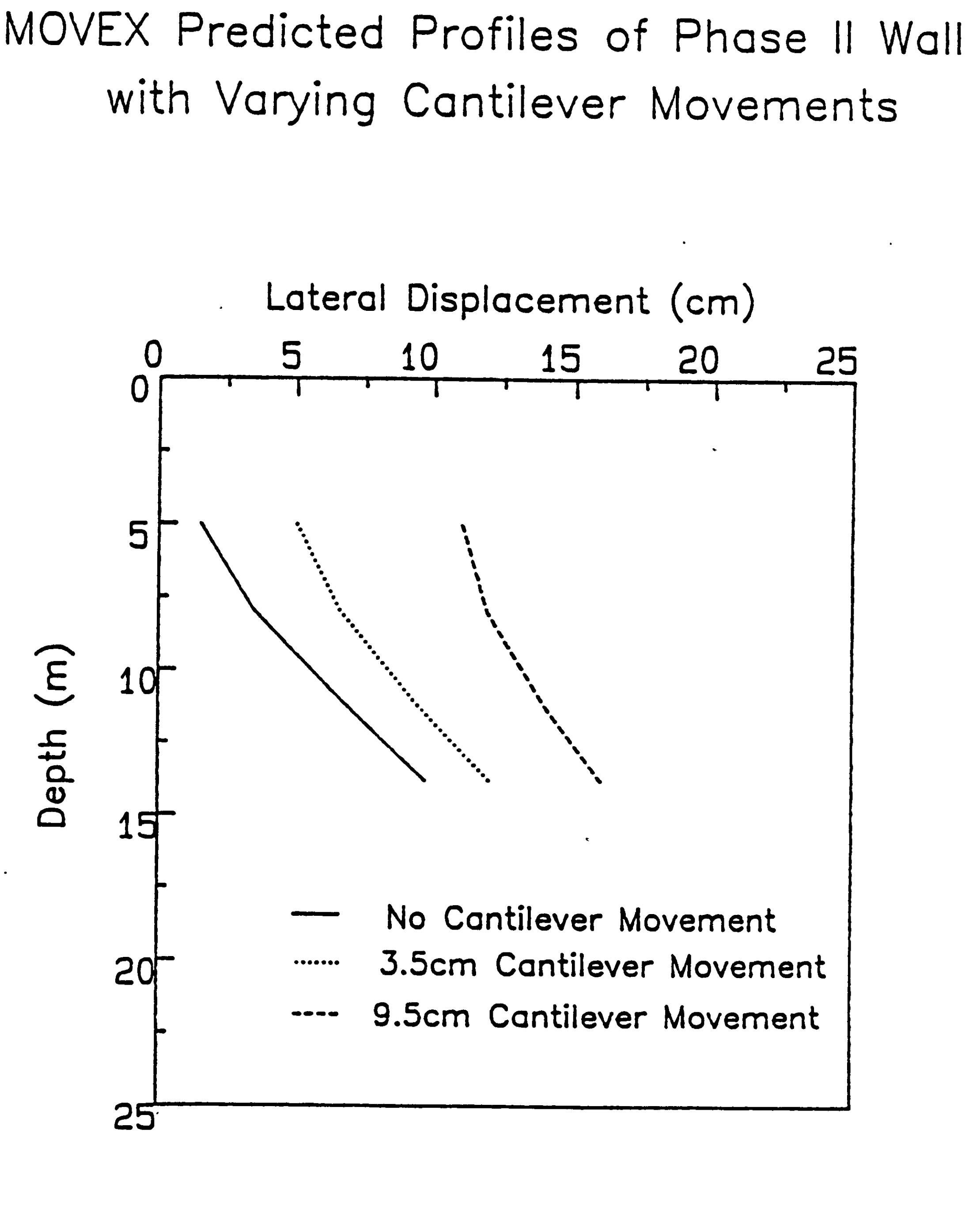



Figure 5.5: Predicted Wall Movements for Given Amounts of Cantilever Movement

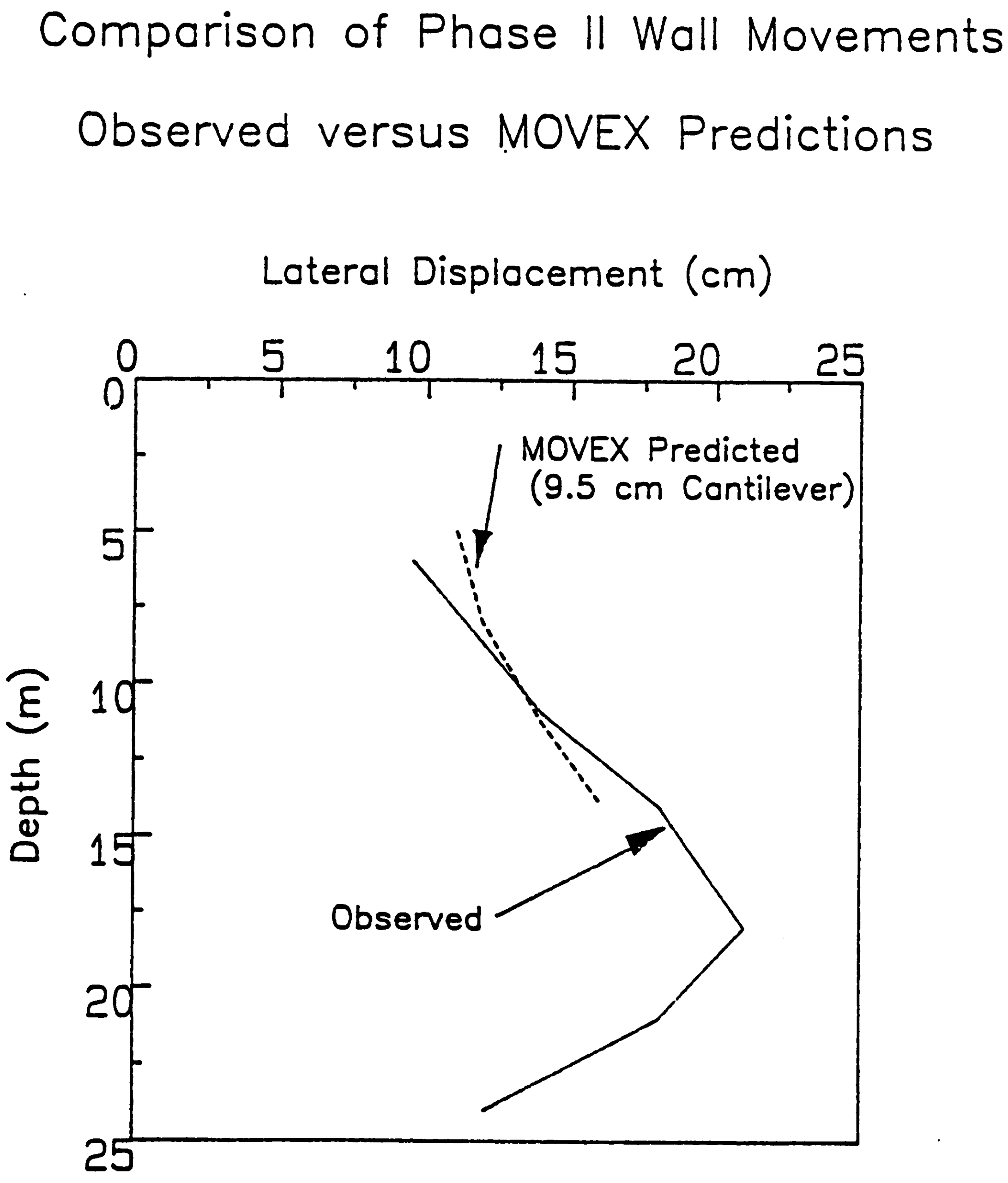



Figure 5.6 - Observed versus Predicted Wall Movements for Equal Cantilever Movements

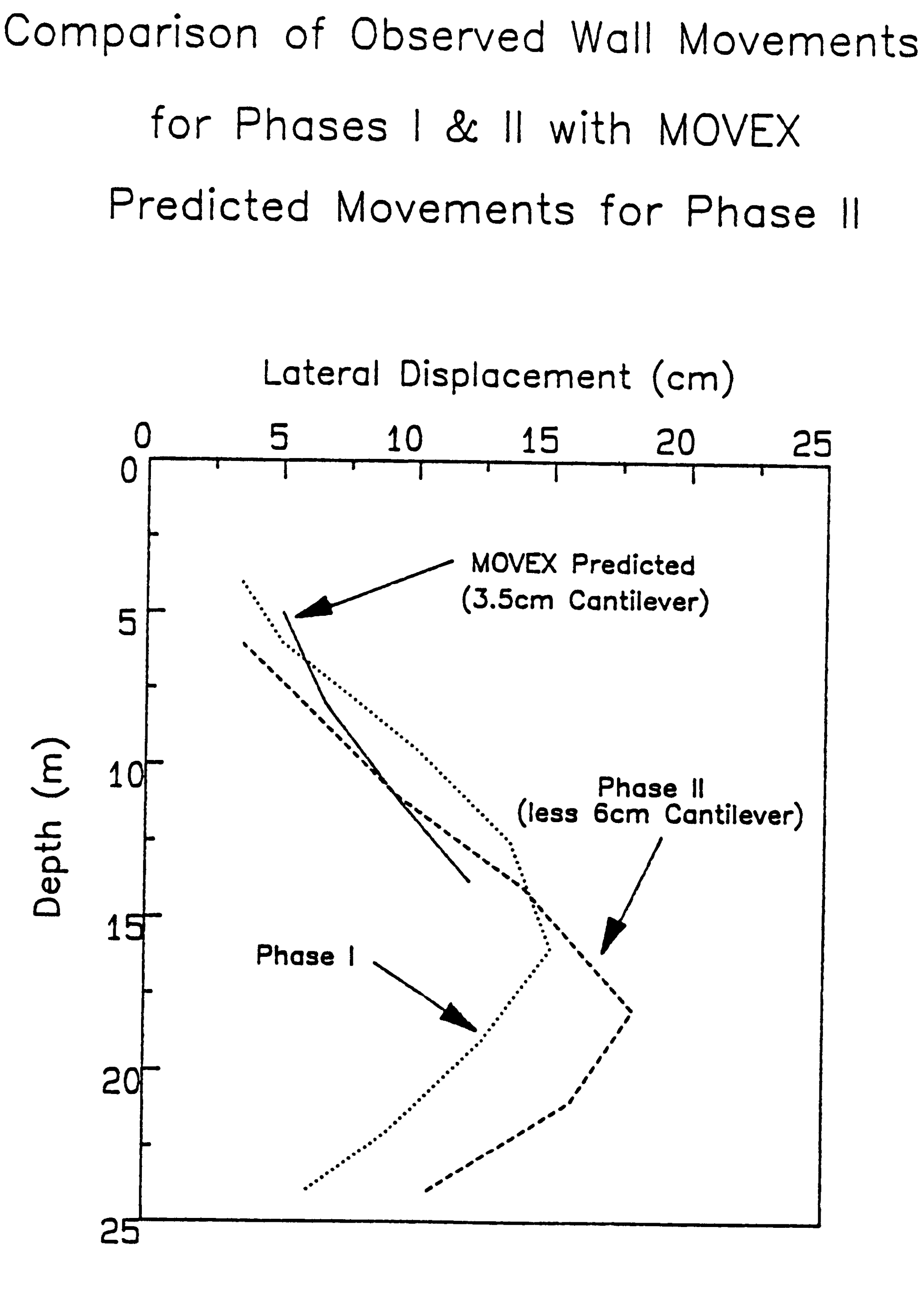



Figure 5.7 - Comparison of Observed versus Predicted Wall Movements adjusted to have Equal Cantilever Wall Movements

PROGRAM MOVEX

Braced Sheetpile Wall in San Francisco, Phase II,
No Cantilever

| | |
|---|---|
| The system of units used is | SI |
| The units of length are - | Meters |
| The units of stress are - | kPa |

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

No Cantilever Movements are Anticipated

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 7.50 | Cohesion | 20.00 |
| Unit Weight | 14.40 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 22.50 | Cohesion | 24.50 |
| Unit Weight | 15.70 | Coh. Increase | 1.31 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 15.00 | Cohesion | 79.00 |
| Unit Weight | 20.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 100.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 41.25 |
| Total length of excavation | 82.50 |
| Final depth of excavation | 13.80 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .601E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 5.00 | .3530E+06 |
| 2 | 8.00 | .3530E+06 |
| 3 | 11.20 | .3530E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 2.93 |
| Nondimensional System Stiffness = | 82.78 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 5.000 |
| Factor of safety against basal heave is | 3.4433 |
| Minimum factor of safety between stages is | 3.4433 |
| Average Strut Stiffness = | 353000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .015 |
| Overall Maximum Lateral Wall Movement is | .015 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 8.000 |
| Factor of safety against basal heave is | 2.4427 |
| Minimum factor of safety between stages is | 2.4427 |
| Average Strut Stiffness = | 353000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .035 |
| Overall Maximum Lateral Wall Movement is | .035 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 11.200 |
| Factor of safety against basal heave is | 1.9104 |
| Minimum factor of safety between stages is | 1.9104 |
| Average Strut Stiffness = | 353000.00 |
| Alpha D = | 1.00 |

| | |
|---|---|
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .068 |
| Overall Maximum Lateral Wall Movement is | .068 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 13.800 |
| Factor of safety against basal heave is | 1.6603 |
| Minimum factor of safety between stages is | 1.6603 |

| | |
|---|---|
| Average Strut Stiffness = | 359533.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.54 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .097 |
| Overall Maximum Lateral Wall Movement is | .097 |

PROGRAM MOVEX

Braced Sheetpile Wall in San Francisco, Phase II,
Cantilever = 9.5cm

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

Expected Cantilever Movement at Top = .114
Anticipated Hinge Depth = 30.00

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 7.50 | Cohesion | 20.00 |
| Unit Weight | 14.40 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 22.50 | Cohesion | 24.50 |
| Unit Weight | 15.70 | Coh. Increase | 1.31 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 15.00 | Cohesion | 79.00 |
| Unit Weight | 20.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 100.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 41.25 |
| Total length of excavation | 82.50 |
| Final depth of excavation | 13.80 |
| Surcharge next to excavation | .00 |

Wall Stiffness (EI) .601E+05

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 5.00 | .3530E+06 |
| 2 | 8.00 | .3530E+06 |
| 3 | 11.20 | .3530E+06 |

MOVEMENT CALCULATIONS

Average Strut Spacing = 2.93
Nondimensional System Stiffness = 82.78

Excavation stage 1

Height of excavation is 5.000
Factor of safety against basal heave is 3.4433
Minimum factor of safety between stages is 3.4433

Average Strut Stiffness = 353000.00
Alpha D = 1.00
Alpha B = 1.70
Alpha S = .75

Lateral Wall Movement at this Stage is .015
Cantilever Movement at this Stage is .095
Total Wall Movement at this Stage is .110
Overall Maximum Lateral Wall Movement is .110

Excavation stage 2

Height of excavation is 8.000
Factor of safety against basal heave is 2.4427
Minimum factor of safety between stages is 2.4427

Average Strut Stiffness = 353000.00
Alpha D = 1.00
Alpha B = 1.70
Alpha S = .75

Lateral Wall Movement at this Stage is .035
Cantilever Movement at this Stage is .084
Total Wall Movement at this Stage is .119
Overall Maximum Lateral Wall Movement is .119

Excavation stage 3

Height of excavation is 11.200

| | |
|---|---|
| Factor of safety against basal heave is | 1.9104 |
| Minimum factor of safety between stages is | 1.9104 |
| Average Strut Stiffness = | 353000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .068 |
| Cantilever Movement at this Stage is | .071 |
| Total Wall Movement at this Stage is | .139 |
| Overall Maximum Lateral Wall Movement is | .139 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 13.800 |
| Factor of safety against basal heave is | 1.6603 |
| Minimum factor of safety between stages is | 1.6603 |
| Average Strut Stiffness = | 359533.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.54 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .097 |
| Cantilever Movement at this Stage is | .062 |
| Total Wall Movement at this Stage is | .159 |
| Overall Maximum Lateral Wall Movement is | .159 |

PROGRAM MOVEX

Braced Sheetpile Wall in San Francisco, Phase II,
Cantilever = 3.5cm

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .042 |
| Anticipated Hinge Depth = | 30.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 7.50 | Cohesion | 20.00 |
| Unit Weight | 14.40 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 22.50 | Cohesion | 24.50 |
| Unit Weight | 15.70 | Coh. Increase | 1.31 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 15.00 | Cohesion | 79.00 |
| Unit Weight | 20.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 100.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 41.25 |
| Total length of excavation | 82.50 |
| Final depth of excavation | 13.80 |
| Surcharge next to excavation | .00 |

| | |
|---|---|
| Wall Stiffness (EI) | .601E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 5.00 | .3530E+06 |
| 2 | 8.00 | .3530E+06 |
| 3 | 11.20 | .3530E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 2.93 |
| Nondimensional System Stiffness = | 82.78 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 5.000 |
| Factor of safety against basal heave is | 3.4433 |
| Minimum factor of safety between stages is | 3.4433 |
| Average Strut Stiffness = | 353000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .015 |
| Cantilever Movement at this Stage is | .035 |
| Total Wall Movement at this Stage is | .050 |
| Overall Maximum Lateral Wall Movement is | .050 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 8.000 |
| Factor of safety against basal heave is | 2.4427 |
| Minimum factor of safety between stages is | 2.4427 |
| Average Strut Stiffness = | 353000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .035 |
| Cantilever Movement at this Stage is | .031 |
| Total Wall Movement at this Stage is | .066 |
| Overall Maximum Lateral Wall Movement is | .066 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 11.200 |

| | |
|---|---|
| Factor of safety against basal heave is | 1.9104 |
| Minimum factor of safety between stages is | 1.9104 |
| Average Strut Stiffness = | 353000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .068 |
| Cantilever Movement at this Stage is | .026 |
| Total Wall Movement at this Stage is | .094 |
| Overall Maximum Lateral Wall Movement is | .094 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 13.800 |
| Factor of safety against basal heave is | 1.6603 |
| Minimum factor of safety between stages is | 1.6603 |
| Average Strut Stiffness = | 359533.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.54 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .097 |
| Cantilever Movement at this Stage is | .023 |
| Total Wall Movement at this Stage is | .120 |
| Overall Maximum Lateral Wall Movement is | .120 |

# Chapter 6

# Case Histories

## 6.1 Introduction

This chapter contains seven case history studies which were used to evaluate the accuracy of MOVEX predictions of movements. The first three cases histories, Cases 1-3, are braced excavations in Chicago summarized by Smith (1986). The remaining studies are of supported excavations in Singapore, where Cases A-C are from Broms, et al (1986), and Case D is from Wong (1987). The seven case histories studied cover a range of excavation support methods, including cross-lot braces, anchored tie-backs, berms and rakers, and slurry wall construction. A summary of the jobs and their support systems is given in Table 6.1.

All of the case histories provided in this thesis were examined using a range of reasonable values of undrained shear strength for each soil layer. There are two reasons for using ranges of soil strengths. First, field sampling and laboratory testing procedures are subject to disturbance, which often result in conservative estimates of undrained shear strength. Second, the actual conditions in the field make perfect evaluation of the shear strength very difficult. For each case analyzed, both high and low values of undrained shear strength were used in the MOVEX program to obtain a range of predicted movements. A

Table 6.1

Summary of Support Systems for Case Histories Analyzed

| Case | Support System |
|---|---|
| 1 | Conventional Cross-Lot Bracing System Sheetpile Wall (Benzal BZ-17) Supported by Two Levels of Steel Pipe Struts |
| 2 | Soldier Beam and Wood Lagging Wall Supported by Three Levels of Earth Berms and Rakers |
| 3 | Combination System Sheetpile Wall (PZ-27) Supported by an Upper Level of Tie-backs and Two Lower Levels of Earth Berms and Rakers |
| A | Conventional Cross-Lot Bracing System Steel Sheetpile Wall (FSP-IIIA) and Six Levels of Steel H-Pile Struts |
| B | Conventional Cross-Lot Bracing System Steel Sheetpile Wall (FSP-IV) and Six Levels of Steel H-Pile Struts |
| C | Conventional Cross-Lot Bracing System Steel Sheetpile Wall (FSP VIL) and Five Levels of Steel H-Pile Struts |
| D | Diaphragm Wall (ie, Slurry Wall) System High Strength Concrete Slurry Wall Supported by Three Levels of High Strength Concrete Struts |

discussion of the shear strengths used and the methods by which they were obtained is provided for both the Chicago and the Singapore studies.

6.2 Chicago Studies, Cases 1-3

The three Chicago case histories presented in this thesis were summarized and evaluated by Smith (1986). These cases were useful because Smith predicted the wall movements for the cases using a previous version of MOVEX. The only alterations made to the MOVEX data files previously used by Smith were those dictated by the new version of MOVEX, namely the cantilever effect data. In the cases presented in this thesis, all soils were assumed isotropic.

Smith (1986) evaluated the undrained shear strength of the clay soils using available test data. The test data were mainly from unconfined compression and pocket penetrometer tests, and some vane shear tests for Case 1. Smith noted that none of these tests is particularly accurate, and to compensate for this, Smith ran the MOVEX analyses based on two sets of undrained shear strength, a low and high range. The low range of shear strengths were those estimated from the test data, per se. To obtain the high range of shear strengths, the low strength values were increased by 30% based on evidence presented in other publications of normalized undrained strength behavior trends. The values of shear strength used by Smith were used for the evaluations in this thesis.

The soil profiles for the three cases are very similar. In general, the top soil layer is a miscellaneous sand and rubble fill. The fill layer for each case is considered to have weight, but no shear strength; this somewhat conservative assumption is applied since the confining pressures in these materials is low and no controls were exercised in their placement. Beneath the fill is a soft to medium silty clay, which is followed by either a stiff to hard silty clay or hardpan. The groundwater table is at a depth of approximately 10 feet for the three excavations studied.

Chicago Studies, Case 1

Case 1 is a conventional cross-lot braced excavation for a two-level parking facility on Congress Street in Chicago, Illinois. The values used to evaluate Case 1 are provided in Table 6.2. Note that the undrained shear strengths of the soils other than the fill layer show high and low values. The values are derived by increasing the low (measured) shear strength values by 30%. The overall excavation dimensions are 185 by 370 feet. Because of the excavation sequence, the length used in the MOVEX analysis is taken as 150 feet. The final excavation depth ranges from 25 to 35 feet, and 30 is used in the MOVEX analysis.

Table 6.2

Values used to Evaluate Case 1

| Parameter | Symbol | Value |
| --- | --- | --- |
| Fill Layer (0-5 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 125 |
| Undrained Shear Strength (psf) | $S_u$ | 0 |
| Clay Layer 1 (5-10 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 90 |
| Undrained Shear Strength (psf) | $S_u$(low) | 600 |
| | $S_u$(high) | 800 |
| Clay Layer 2 (10-59 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 120 |
| Undrained Shear Strength (psf) | $S_u$(low) | 700 |
| | $S_u$(high) | 900 |
| Clay Layer 3 (59-72 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 120 |
| Undrained Shear Strength (psf) | $S_u$(low) | 4500 |
| | $S_u$(high) | 6000 |
| Wall Stiffness (psf/ft) | EI | $3.8 \times 10^7$ |
| Strut Stiffness (psf/ft) | | |
| Strut 1 (at 9 ft) | AE/L | $6.48 \times 10^5$ |
| Strut 2 (at 25 ft) | AE/L | $8.08 \times 10^5$ |
| Excavation Width (ft) | B | 185 |
| Excavation Length (ft) | L | 150 |
| Final Excavation Depth (ft) | D | 30 |
| Depth to Firm Layer (ft) | | 59 |
| Surcharge Next to Excavation (psf) | q | 100 |
| Cantilever Movement Top of Wall (ft) | CEM | 0.083 |
| Cantilever Hinge Depth (ft) | CEH | 50 |
| Unit Weight of Water (pcf) | $\gamma_w$ | 62.4 |

Two levels of 24-inch diameter steel pipe struts were used to support the steel sheetpile wall. Cantilever wall movements of about one inch were observed at the top of the wall.

The observed and predicted movements are shown in the plot in Figure 6.1. The MOVEX results are given in Tables C.1 and C.2 of Appendix C. The MOVEX results show values of FS as low as 1.46 for the low strength case at the full excavation depth. The predictions appear to be fairly accurate, with the high strength assumption predictions closer to the observed than the low strength values.

Chicago Studies, Case 2

Case 2 is an excavation for a 35-story office building on the north bank of the Chicago River in Chicago, Illinois. The excavation support system is a soldier beam and wood lagging wall supported by earth berms and rakers. The geometry of this case is rather complicated, but the generalized configuration is listed in Table 6.3. At the top of the wall considered is a pile supported retaining wall which was placed to support the street. The excavation dimensions are 120 by 210 feet, and the final depth is 50 feet below street level. Smith (1986) reduced the final depth to be used in the MOVEX analyses to 32.5 feet to account for the strength of the retaining wall. The high and low shear strength values were obtained as

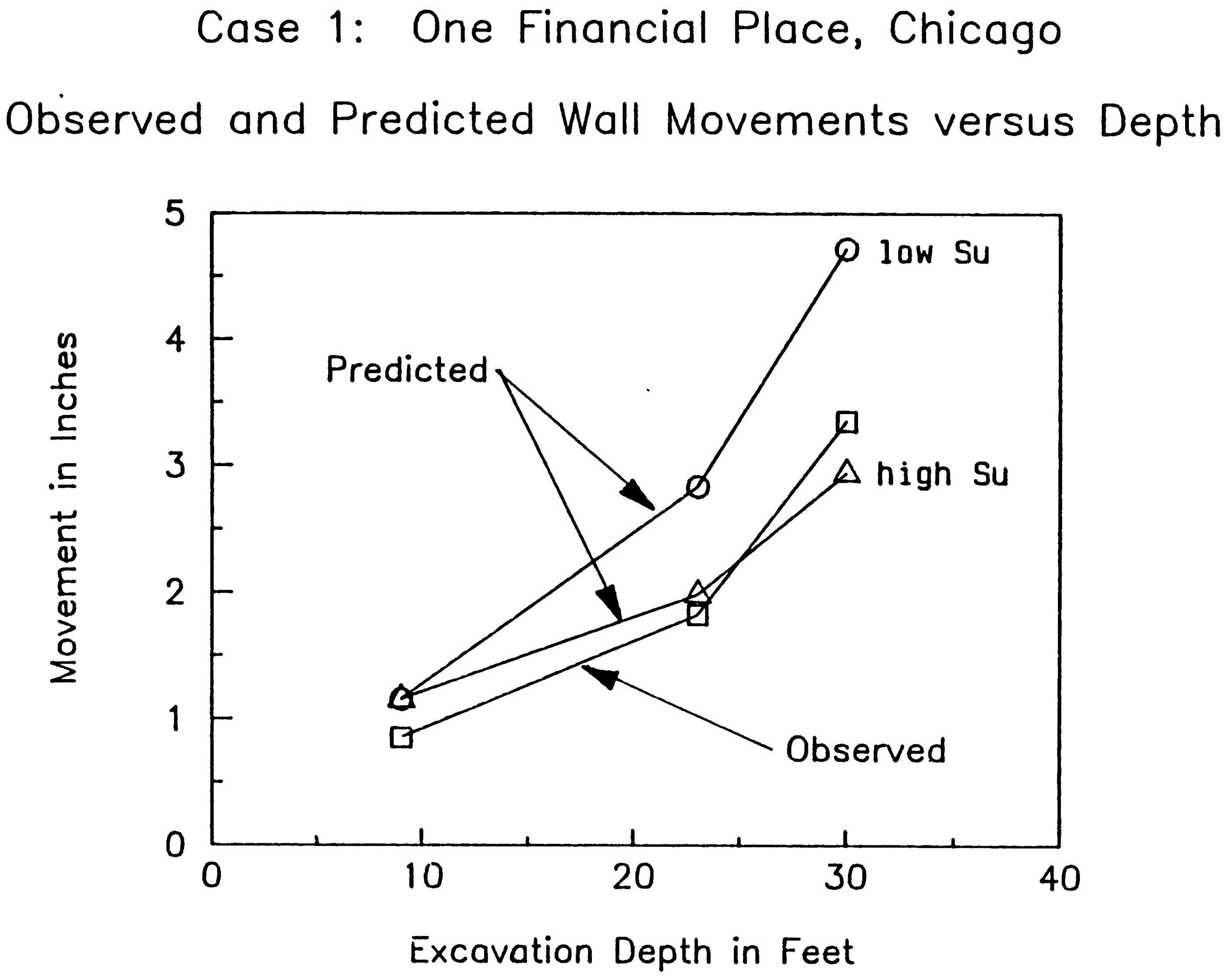



Figure 6.1 - MOVEX Predictions for Case 1 (after Smith, 1986)

described for Case 1. The cantilever movements observed at the top of the wall were 4 inches, and are large due to the earth berm and raker system of support.

The observed and predicted movements are shown in Figure 6.2, and the MOVEX results are provided in Tables C.3 and C.4 of Appendix C. This system shows large displacements because the excavation was made to the full depth in the center of the site before the berms and rakers were erected to support the wall. The retaining wall may have also contributed excess surcharge loads to the support system.

It is important to note the method with which Smith (1986) plotted the observed movements. Even though the soil at the center of the site had been excavated, she defined the excavation stages as the depth at which the soil directly adjacent to the wall was removed and a raker installed. Although her method was used for this thesis, an alternate method could be used in which the excavation stage depths are defined by a factored depth based on the volume of soil removed over the entire site. This alternate method would show movements more in line with conventional systems, that is, the movements would be small at early stages and increase with depth. If the alternate method is used, the movements may end up more in line with the MOVEX predicted movements.

Table 6.3

Values used to Evaluate Case 2

| Parameter | Symbol | Value |
|---|---|---|
| Fill Layer (0-10 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 120 |
| Undrained Shear Strength (psf) | $S_u$ | 0 |
| Clay Layer 1 (10-48.5 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 110 |
| Undrained Shear Strength (psf) | $S_u$(low) | 600 |
| | $S_u$(high) | 800 |
| Clay Layer 2 (48.5-81 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 110 |
| Undrained Shear Strength (psf) | $S_u$(low) | 1500 |
| | $S_u$(high) | 2000 |
| Wall Stiffness (psf/ft) | EI | $1.36 \times 10^7$ |
| Strut Stiffness (psf/ft) | | |
| Strut 1 (at 3 ft) | AE/L | $1.41 \times 10^6$ |
| Strut 2 (at 14 ft) | AE/L | $2.09 \times 10^6$ |
| Strut 3 (at 25 ft) | AE/L | $2.09 \times 10^5$ |
| Excavation Width (ft) | B | 120 |
| Excavation Length (ft) | L | 210 |
| Final Excavation Depth (ft) | D | 32.5 |
| Depth to Firm Layer (ft) | | 48.5 |
| Surcharge Next to Excavation (psf) | q | 100 |
| Cantilever Movement Top of Wall (ft) | CEM | 0.33 |
| Cantilever Hinge Depth (ft) | CEH | 45 |
| Unit Weight of Water (pcf) | $\gamma_w$ | 62.4 |

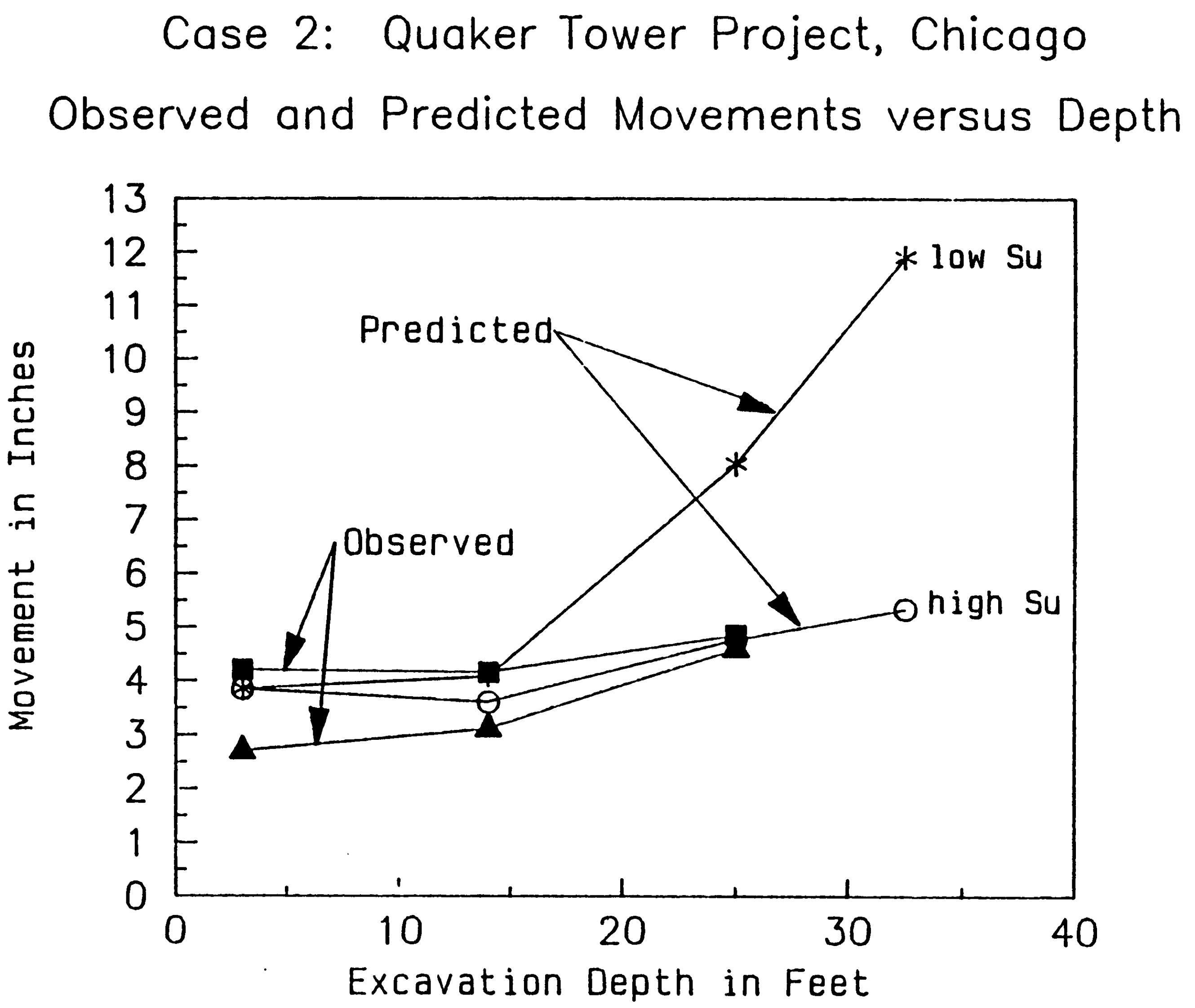



Figure 6.2 - MOVEX Predictions for Case 2 (after Smith, 1986)

Chicago Studies, Case 3

Case 3 is a 35-foot-deep excavation for a 68-story office building on Michigan Avenue in Chicago, Illinois. This case is presented earlier in this thesis as example 3.4.2, and a cross-section is shown in Figure 3.2. The plan dimensions of the site are 230 by 440 feet. This excavation is interesting because it has a combination support system made up of a sheetpile wall supported by an upper row of tie-backs, and two lower levels of earth berms and rakers. The excavation depth used by Smith (1986) and used in the MOVEX analyses is 29 feet because the initial excavation was a slope cut at 1.5 to 1 to reach the level where the wall was installed (see Figure 3.2). Initial cantilever movements of one inch, a rough average of the cantilever movements exhibited by the three inclinometer readings provided in Smith (1986), were used for the analyses. Again, high and low values of shear strength were used in the analyses.

Figure 6.3 shows the predicted and observed movements for Case 3, and the MOVEX results are provided in Tables C.5 and C.6 of Appendix C. The cantilever movements dominate the MOVEX predictions for the first two stages, but at stages 3 and 4, there is an obvious difference in movements for the high and low shear strength cases. As expected, the low $S_u$ case shows larger movements. The

Table 6.4

| Values used to Evaluate Case 3 | | |
|---|---|---|
| Parameter | Symbol | Value |
| Fill Layer (0-20 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 110 |
| Undrained Shear Strength (psf) | $S_u$ | 0 |
| Clay Layer 1 (20-40 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 125 |
| Undrained Shear Strength (psf) | $S_u$(low) | 600 |
| | $S_u$(high) | 800 |
| Clay Layer 2 (40-60 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 125 |
| Undrained Shear Strength (psf) | $S_u$(low) | 700 |
| | $S_u$(high) | 1000 |
| Clay Layer 3 (60-80 ft) | | |
| Total Unit Weight (pcf) | $\gamma$ | 125 |
| Undrained Shear Strength (psf) | $S_u$(low) | 1500 |
| | $S_u$(high) | 2000 |
| Wall Stiffness (psf/ft) | EI | $3.8 \times 10^7$ |
| Strut Stiffness (psf/ft) | | |
| Strut 1 (at 4 ft) | AE/L | $5.08 \times 10^2$ |
| Strut 2 (at 12 ft) | AE/L | $1.11 \times 10^6$ |
| Strut 3 (at 24 ft) | AE/L | $1.59 \times 10^6$ |
| Excavation Width (ft) | B | 230 |
| Excavation Length (ft) | L | 440 |
| Final Excavation Depth (ft) | D | 29 |
| Depth to Firm Layer (ft) | | 60 |
| Surcharge Next to Excavation (psf) | q | 650 |
| Cantilever Movement Top of Wall (ft) | CEM | 0.083 |
| Cantilever Hinge Depth (ft) | CEH | 30 |
| Unit Weight of Water (pcf) | $\gamma_w$ | 62.4 |

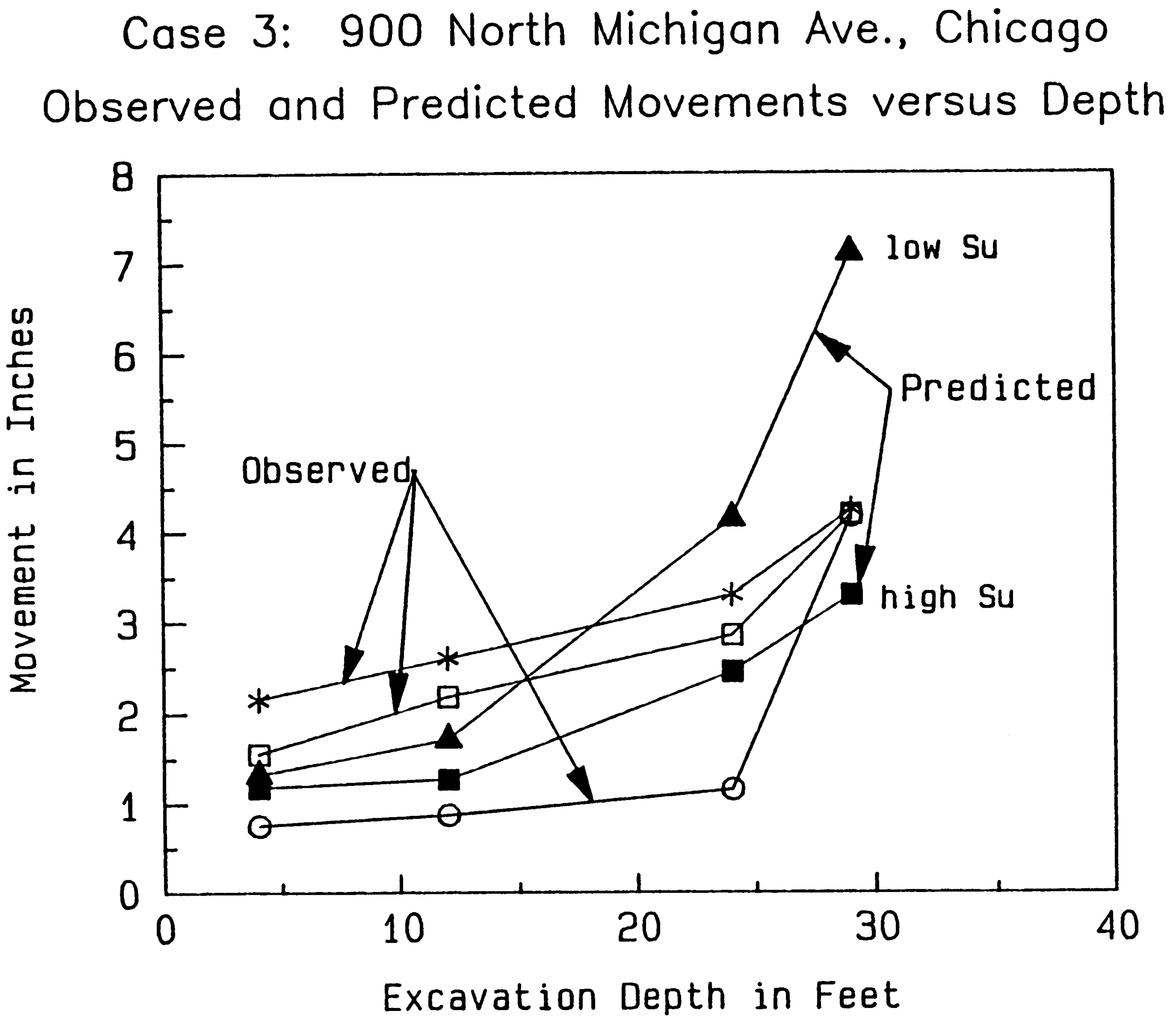



Figure 6.3 - MOVEX Predictions for Case 3 (after Smith, 1986)

MOVEX predicted movements, using a high $S_u$ value, are in good agreement with the observed movements. As for Case 2, the excavation depth in the center of the site preceded excavation along the sheetpile walls. The depths used to define the excavation stages did not take into account the earlier excavations, and were taken strictly as the depth at which the soil was removed adjacent to the wall and a raker (or tie-back) installed. The large movements exhibited at the final excavation stage are in part due to construction delays caused by a strike.

## 6.3 Singapore Studies

Three of the Singapore Studies presented in this thesis, Cases A, B, and C, are provided by Broms, et al (1986). Case D was provided by Wong (1987), and is scheduled to be published in the 1988 proceedings of an Australia-New Zealand Conference. The Singapore case histories B-D are from projects for the construction of a subway system, while project A is assumed by the author to be a building foundation.

The soil profiles for the Singapore cases are made up of essentially the same materials. The top soil layer is generally a sandy fill 1 to 3 meters thick. Underlying the fill is a soft marine clay. The slightly overconsolidated marine clay is made up of two distinct layers separated by a thin sand layer. The upper marine clay varies in thickness, from 3 to 23 meters for the cases studied. The sand layer found between members of the marine clay is consistently about 1 to 3 meters thick. The lower marine clay is generally 7 meters thick, underlain by a stiff sandy silt which is basically a decomposed granite.

The shear strengths of the soils mentioned above were evaluated for this thesis based on the values provided in the respective papers, and by estimating the shear strengths of the clay layers using the relationship $(S_u/\sigma_v{}') = 0.22$ (Equation 6.1) from Holtz and Kovacs (1981). The shear strengths provided in the papers were evaluated by laboratory unconsolidated-undrained triaxial shear tests. For purposes of comparison, the shear strengths calculated with equation 6.1 are termed $S_u$(low), and the laboratory values given in Broms, et al (1986) and Wong (1987) are termed $S_u$(avg). The high values of shear strength used in the MOVEX analyses are derived from the larger of $S_u$(low) and $S_u$(avg). It should be noted that the shear strengths for the Singapore clays increase almost linearly with depth, and the larger value of $S_u$ is taken at both the top and the bottom of the layer such that $S_u$(high) may have the value of $S_u$(avg) at the top of the layer and $S_u$(low) at the bottom of the layer, or some combination thereof. Tables showing the derivation of the shear strength values are provided for each case. The sand layers in all of the cases were designated a cohesion of 10 kPa rather than using the "equivalent cohesion" concept outlined in Chapter 3. The value of 10 kPa is conservative for all of the cases, and this is shown in the shear strength calculations provided for each case.

### 6.3.1 Telecom Building, Case A

This case is a conventional cross-lot braced deep excavation located in the central business district of Singapore. The values used to evaluate the project are given in Table 6.5. The final excavation depth is 11.1m, and the plan dimensions are 42.6 by 27 meters. Six levels of struts support the steel sheetpile wall, with the vertical spacings given in Table 6.5. The undrained shear strengths listed in Table 6.5 were derived as shown in Table 6.6. Cantilever movements of 0.4 inch were observed at the top of the wall, and were included in the MOVEX computations.

The MOVEX predicted wall movements and the observed wall movements are plotted in Figure 6.4. As mentioned earlier, the observed movement is plotted as a single point at the final excavation depth because only the final wall movements were available. Broms, et al (1986) indicate that the sheetpile experienced local yielding when the wall movements reached the maximum values. This is probably why the movements are shown to be very large at the final

Table 6.5

**Values used to Evaluate Case A**

| Parameter | Symbol | Value |
|---|---|---|
| Fill Layer (0-1m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 18 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 0+4h |
| | $S_u$(high) | 10 |
| Upper Marine Clay Layer (1-24m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 16 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 4+1.4h |
| | $S_u$(high) | 20+0.8h |
| Sand Layer (24-26m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 18 |
| Undrained Shear Strength (kPa) | $S_u$ | 10 |
| Lower Marine Clay Layer (26-33m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 18 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 40+1.9h |
| | $S_u$(high) | 40+5.7h |
| Stiff Sandy Silt (33-53m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 18.5 |
| Undrained Shear Strength (kPa) | $S_u$ | 70 |
| Wall Stiffness (kPa/m) | EI | $1.4 \times 10^4$ |
| Strut Stiffness (kPa/m) | | |
| Strut 1 (at 1m) | AE/L | $1.29 \times 10^5$ |
| Strut 2 (at 3.5m) | AE/L | $1.29 \times 10^5$ |
| Strut 3 (at 5.25m) | AE/L | $1.59 \times 10^5$ |
| Strut 4 (at 6.9m) | AE/L | $1.59 \times 10^5$ |
| Strut 5 (at 8.25m) | AE/L | $1.59 \times 10^5$ |
| Strut 6 (at 9.75m) | AE/L | $1.59 \times 10^5$ |
| Excavation Width (m) | B | 27 |
| Excavation Length (m) | L | 42.6 |

Table 6.5 (cont.)

| Parameter | Symbol | Value |
|---|---|---|
| Final Excavation Depth (m) | D | 11.1 |
| Depth to Firm Layer (m) | | 35 |
| Surcharge Next to Excavation (kPa) | q | 0 |
| Cantilever Movement Top of Wall (m) | CEM | 0.01 |
| Cantilever Hinge Depth (m) | CEH | 20 |
| Unit Weight of Water (kPa/m) | $\gamma_w$ | 9.81 |

Table 6.6

## Evaluation of Shear Strength Ranges for Case A

| Layer | Depth | $\gamma$ | $S_u$ | $\sigma_v'$ | $S_u$(low) |
|---|---|---|---|---|---|
| Fill | 0<br>1 | 18 | 10 | -<br>18 | 0<br>4 |
| Upper Marine Clay | 1<br>25 | 16 | 20-40 | 18<br>167 | 4<br>37 |
| Loose Sand | 25<br>27 | 18 | - | 167<br>183 | |
| Lower Marine Clay | 27<br>34 | 18 | 40-80 | 183<br>240 | 40<br>53 |

| Layer | $S_u$(low) | $S_u$(avg) | $S_u$(high) |
|---|---|---|---|
| Fill | 0 + 4h | 10 | 10 |
| Upper Clay | 4 + 1.4h | 30 | 20 + 0.8h |
| Lower Clay | 40 + 1.9h | 60 | 40 + 5.7h |

Sand: $C_{eq}$ = "Equivalent Cohesion" = $\sigma_v' K_0 \tan\phi$, and
$\phi = 30$, $K_0 = 0.9$, so $C_{eq}$ = 95 kPa
Designated Shear Strength = 10 kPa

$S_u$(low) = (0.22) $\sigma_v'$
$S_u$(avg) is the average given in Broms, et al (1986)
$S_u$(high) is the higher of $S_u$(low) and $S_u$(high) with depth
Water Table is at 1m depth, and $\gamma_w$ = 9.81 kPa/m

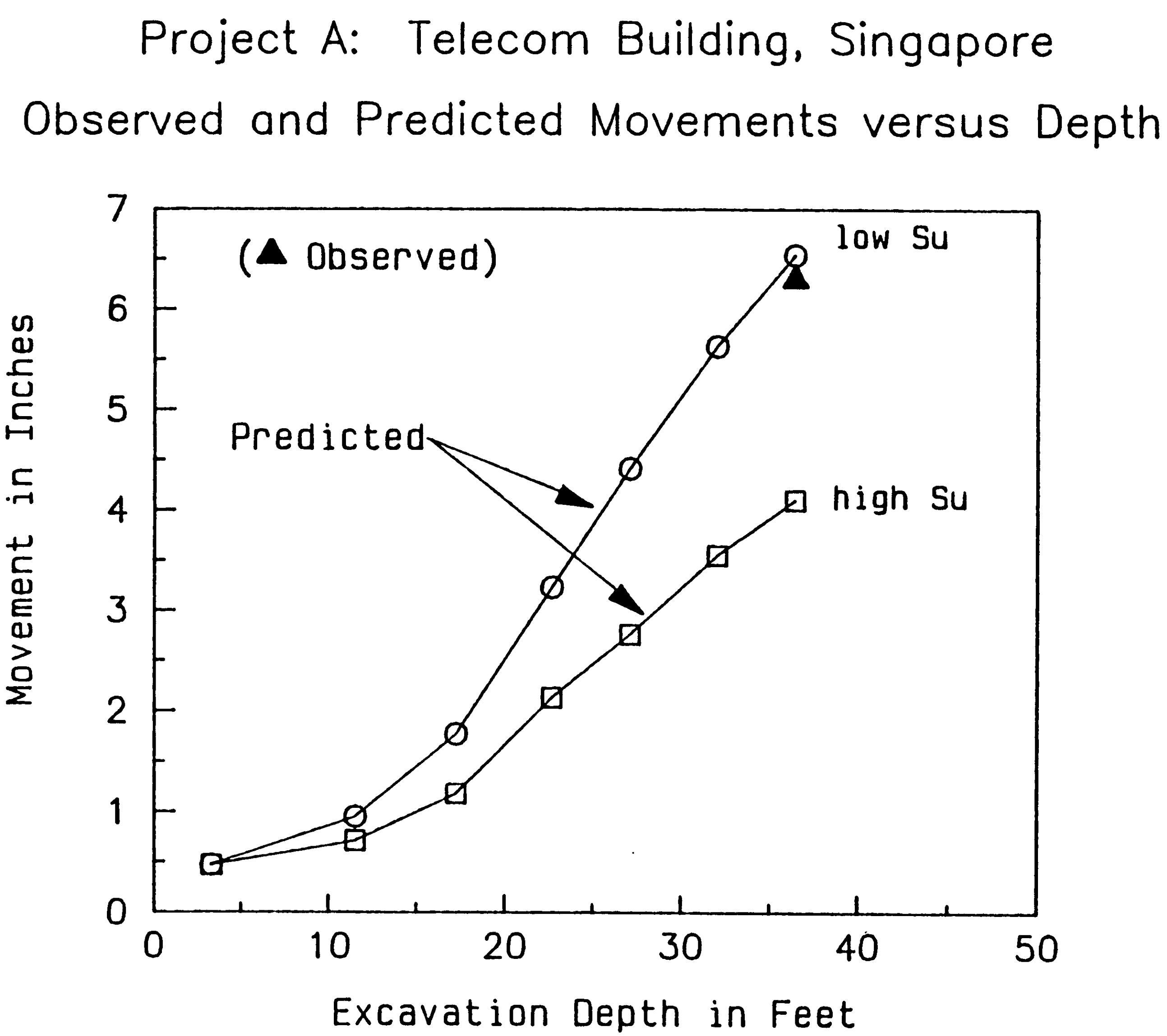



Figure 6.4 - MOVEX Predictions for Case A

depth. The MOVEX predicted movements compare well with the observed movement considering MOVEX did not account for sheetpile yielding.

The FS at the final depth for the low $S_u$ case is 0.94, while for the high $S_u$ case it is 1.2, from Tables C.8 and C.7, respectively. A FS lower than 1 indicates that failure may be forthcoming. The base of the excavation did experience small amounts of heave, 3 to 4 inches, and so the calculated values of FS seem to correspond well with the observed behavior.

Measurements of ground settlements are also provided in Broms, et al (1986). The maximum measured surface movement was about 1% of the final excavation depth (0.11m or 4.4 inches), and it occurred at a distance from the excavation of approximately 50% of the final excavation depth (5.6m or 18 feet). MOVEX predicts maximum surface settlements of 0.14m (5.5 inches) and 0.17m (6.7 inches) for the $S_u$(low) and $S_u$(high) cases at distances of 5.6m from the excavation. The range of predicted surface settlement values are quite accurate for this case.

### 6.3.2 Novena Station, Case B

Case B is a conventional cross-lot braced excavation for a subway station just outside the central business district of Singapore. The final depth of the excavation is 14.7m, and the plan dimensions are 200 by 35 meters. The values used to evaluate Case B are provided in Table 6.7, and the range of shear strengths used is given in Table 6.8. The steel sheetpile walls are supported by six levels of steel h-pile struts. The soil profile varies considerably across the site. On the east side, the soil profile is similar to that seen in Case A, with several meters of soft clay. On the west side, nearly the entire length of the sheetpiles were embedded in the decomposed granite. The profile for the east side is used in the analyses because it is the most critical profile. The first excavation stage was excavated about 2m (6.5 feet), which caused large cantilever movements at the top of the wall and large bending moments in the sheetpile wall. The yield strength of the wall was exceeded by the third excavation stage, which contributed to large overall movements. The first four levels of struts experienced deflections of up to 0.05m (2 inches) after installation.

The observed and predicted wall movements are shown in Figure 6.5. The movements predicted for the $S_u$(low) and $S_u$(high) cases were very similar (see Tables C.9 and C.10) and so only one set was plotted in the figure. The cantilever movements dominate the predicted movements for the first strut levels, and then the movements increase with depth. The MOVEX deflection values are reasonable in

Table 6.7

Values used to Evaluate Case B

| Parameter | Symbol | Value |
| --- | --- | --- |
| Fill Layer (0-2m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 15 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 0+2.2h |
| | $S_u$(high) | 10 |
| Upper Marine Clay Layer (2-5m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 14 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 4.4+0.9h |
| | $S_u$(high) | 10 |
| Sand Layer (5-6.5m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 17 |
| Undrained Shear Strength (kPa) | $S_u$ | 10 |
| Lower Marine Clay Layer (6.6-14m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 15 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 10+1.1h |
| | $S_u$(high) | 10+1.1h |
| Stiff Sandy Silt (14-34m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 18.5 |
| Undrained Shear Strength (kPa) | $S_u$ | 70 |
| Wall Stiffness (kPa/m) | EI | $2.34 \times 10^4$ |
| Strut Stiffness (kPa/m) | | |
| Strut 1 (at 1m) | AE/L | $9.97 \times 10^4$ |
| Strut 2 (at 3m) | AE/L | $9.97 \times 10^4$ |
| Strut 3 (at 5.5m) | AE/L | $1.22 \times 10^5$ |
| Strut 4 (at 7.5m) | AE/L | $1.22 \times 10^5$ |
| Strut 5 (at 9.5m) | AE/L | $1.22 \times 10^5$ |
| Strut 6 (at 11.8m) | AE/L | $1.22 \times 10^5$ |
| Excavation Width (m) | B | 35 |
| Excavation Length (m) | L | 200 |

Table 6.7 (cont.)

| Parameter | Symbol | Value |
|---|---|---|
| Final Excavation Depth (m) | D | 14.7 |
| Depth to Firm Layer (m) | | 14 |
| Surcharge Next to Excavation (kPa) | q | 0 |
| Cantilever Movement Top of Wall (m) | CEM | 0.1 |
| Cantilever Hinge Depth (m) | CEH | 30 |
| Unit Weight of Water (kPa/m) | $\gamma_w$ | 9.81 |

Table 6.8

Evaluation of Shear Strength Ranges for Case B

| Layer | Depth | $\gamma$ | $S_u$ | $\sigma_v'$ | $S_u$(low) |
|---|---|---|---|---|---|
| Fill | 0 | 15 | 10 | - | 0 |
| | 2 | | | 20 | 4.4 |
| Upper | 2 | 14 | 10 | 20 | 4.4 |
| Marine Clay | 5 | | | 33 | 7.2 |
| Loose | 5 | 17 | - | 33 | |
| Sand | 6.5 | | | 44 | |
| Lower | 6.5 | 15 | 15 | 44 | 9.6 |
| Marine Clay | 14 | | | 82 | 18 |

| Layer | $S_u$(low) | $S_u$(avg) | $S_u$(high) |
|---|---|---|---|
| Fill | 0 + 2.2h | 10 | 10 |
| Upper Clay | 4.4 + 0.9h | 10 | 10 |
| Lower Clay | 10 + 1.1h | 15 | 10 + 1.1h |

Sand: $C_{eq}$ = "Equivalent Cohesion" = $\sigma_v' K_0 \tan\phi$, and
$\phi$ = 30, $K_0$= 0.9, so $C_{eq}$ = 20 kPa
Designated Shear Strength = 10 kPa

$S_u$(low) = $(0.22)\,\sigma_v'$
$S_u$(avg) is the average given in Broms, et al (1986)
$S_u$(high) is the higher of $S_u$(low) and $S_u$(high) with depth
Water Table is at 1m depth, and $\gamma_w$ = 9.81 kPa/m

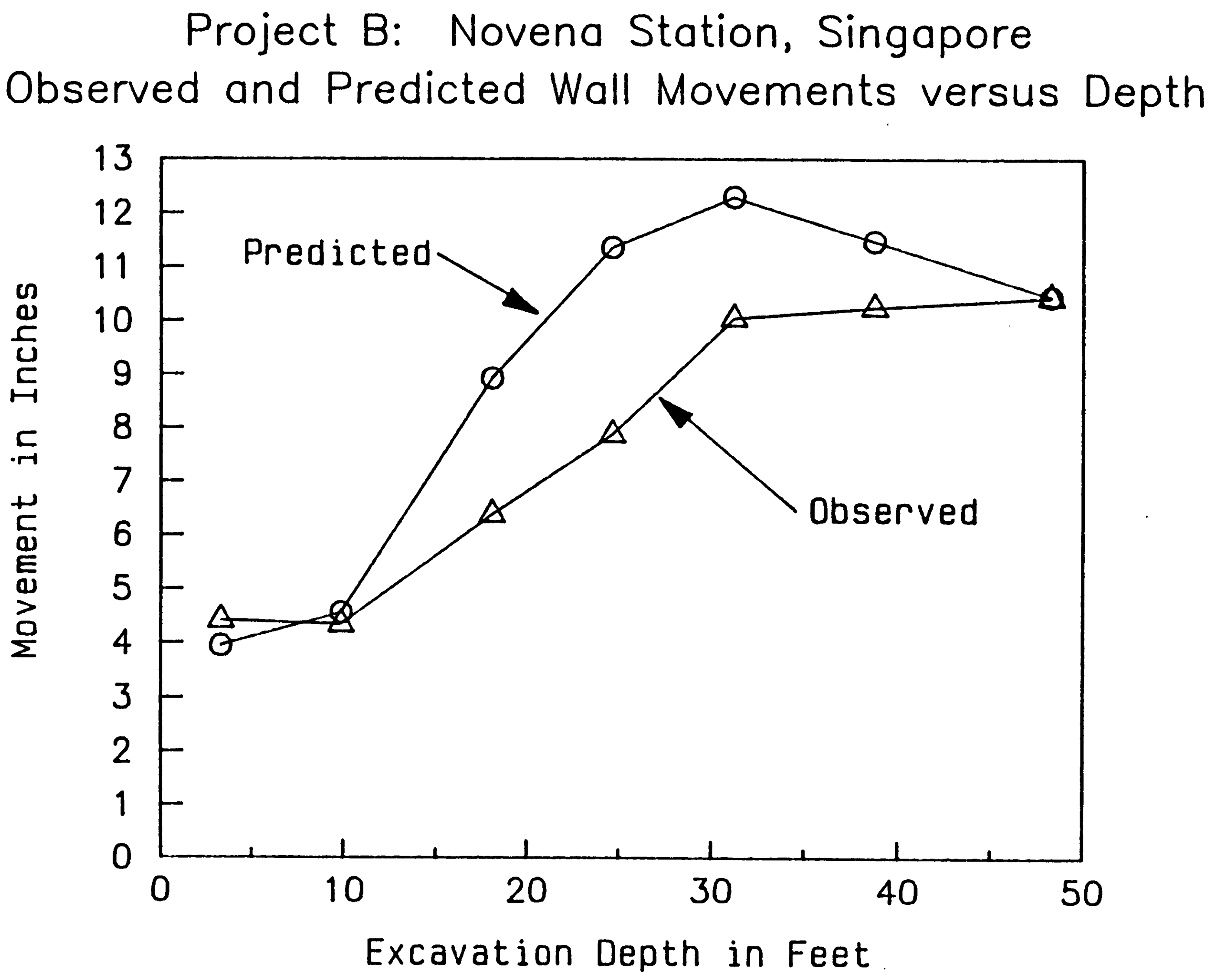



Figure 6.5 - MOVEX Predictions for Case B

terms of modeling an excavation in which good construction methods are used.

6.3.3 Newton Crossover, Case C

The Newton Crossover project is about one half mile from the Case B project. The excavation length is 26m, and the width varies from 6 to 12m. The average width (9m) was used in the MOVEX analyses. The final depth of the excavation is 15m. The parameters used in the MOVEX analyses are provided in Table 6.9, and the shear strength ranges are given in Table 6.10. The actual soil profile varied widely over the site, and Broms, et al (1986) had difficulties modeling the behavior of this excavation using finite element analyses.

The observed and predicted maximum wall movements are plotted in Figure 6.6. The large cantilever movements at the top of the wall are due to late installation of the first level of struts; the struts were placed after 2 to 2.5 meters (6.6 to 8.2 feet) of excavation took place. Large movements at the final excavation stage can also be attributed to about 2.5m of overexcavation before the final level of struts were placed. The MOVEX predictions for this case are larger than the observed movements due to the low FS calculated for the excavation.

The MOVEX predictions suggest that the excavation should fail based on the FS values (see printouts in Tables

Table 6.9

Values used to Evaluate Case C

| Parameter | Symbol | Value |
|---|---|---|
| Fill Layer (0-1.4m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 17 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 0+3.1h |
| | $S_u$(high) | 30 |
| Upper Marine Clay Layer (1.4-10m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 15 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 4.4+1.1h |
| | $S_u$(high) | 10+0.5h |
| Sand Layer (10-13m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 17 |
| Undrained Shear Strength (kPa) | $S_u$ | 10 |
| Lower Marine Clay Layer (13-20m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 15 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 19+1.1h |
| | $S_u$(high) | 19+1.1h |
| Stiff Sandy Silt (20-55m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 18.5 |
| Undrained Shear Strength (kPa) | $S_u$ | 70 |
| Wall Stiffness (kPa/m) | EI | $4.56 \times 10^4$ |
| Strut Stiffness (kPa/m) | | |
| Strut 1 (at 1.5m) | AE/L | $1.82 \times 10^5$ |
| Strut 2 (at 5m) | AE/L | $2.4 \times 10^5$ |
| Strut 3 (at 7.5m) | AE/L | $3.88 \times 10^5$ |
| Strut 4 (at 10.5m) | AE/L | $3.88 \times 10^5$ |
| Strut 5 (at 13m) | AE/L | $3.88 \times 10^5$ |
| Excavation Width (m) | B | 9 |
| Excavation Length (m) | L | 26 |

Table 6.9 (cont.)

| Parameter | Symbol | Value |
|---|---|---|
| Final Excavation Depth (m) | D | 15 |
| Depth to Firm Layer (m) | | 55 |
| Surcharge Next to Excavation (kPa) | q | 0 |
| Cantilever Movement Top of Wall (m) | CEM | 0.068 |
| Cantilever Hinge Depth (m) | CEH | 16 |
| Unit Weight of Water (kPa/m) | $\gamma_w$ | 9.81 |

Table 6.10

Evaluation of Shear Strength Ranges for Case C

| Layer | Depth | $\gamma$ | $S_u$ | $\sigma_v'$ | $S_u$(low) |
|---|---|---|---|---|---|
| Fill | 0<br>1.4 | 17 | 30 | -<br>20 | 0<br>4.4 |
| Upper Marine Clay | 1.4<br>10 | 15 | 10 | 20<br>64.5 | 4.4<br>14.2 |
| Loose Sand | 10<br>13 | 17 | - | 64.5<br>86.1 | |
| Lower Marine Clay | 13<br>20 | 15 | 15 | 86.1<br>122.4 | 19<br>27 |

| Layer | $S_u$(low) | $S_u$(avg) | $S_u$(high) |
|---|---|---|---|
| Fill | 0 + 3.1h | 30 | 30 |
| Upper Clay | 4.4 + 1.1h | 10 | 10 + 0.5h |
| Lower Clay | 19 + 1.1h | 15 | 19 + 1.1h |

Sand: $C_{eq}$ = "Equivalent Cohesion" = $\sigma_v' K_0 \tan\phi$, and
$\phi$ = 30, $K_0$ = 0.9, so $C_{eq}$ = 40 kPa
Designated Shear Strength = 10 kPa

$S_u$(low) = (0.22) $\sigma_v'$
$S_u$(avg) is the average given in Broms, et al (1986)
$S_u$(high) is the higher of $S_u$(low) and $S_u$(high) with depth
Water Table is at 1m depth, and $\gamma_w$ = 9.81 kPa/m

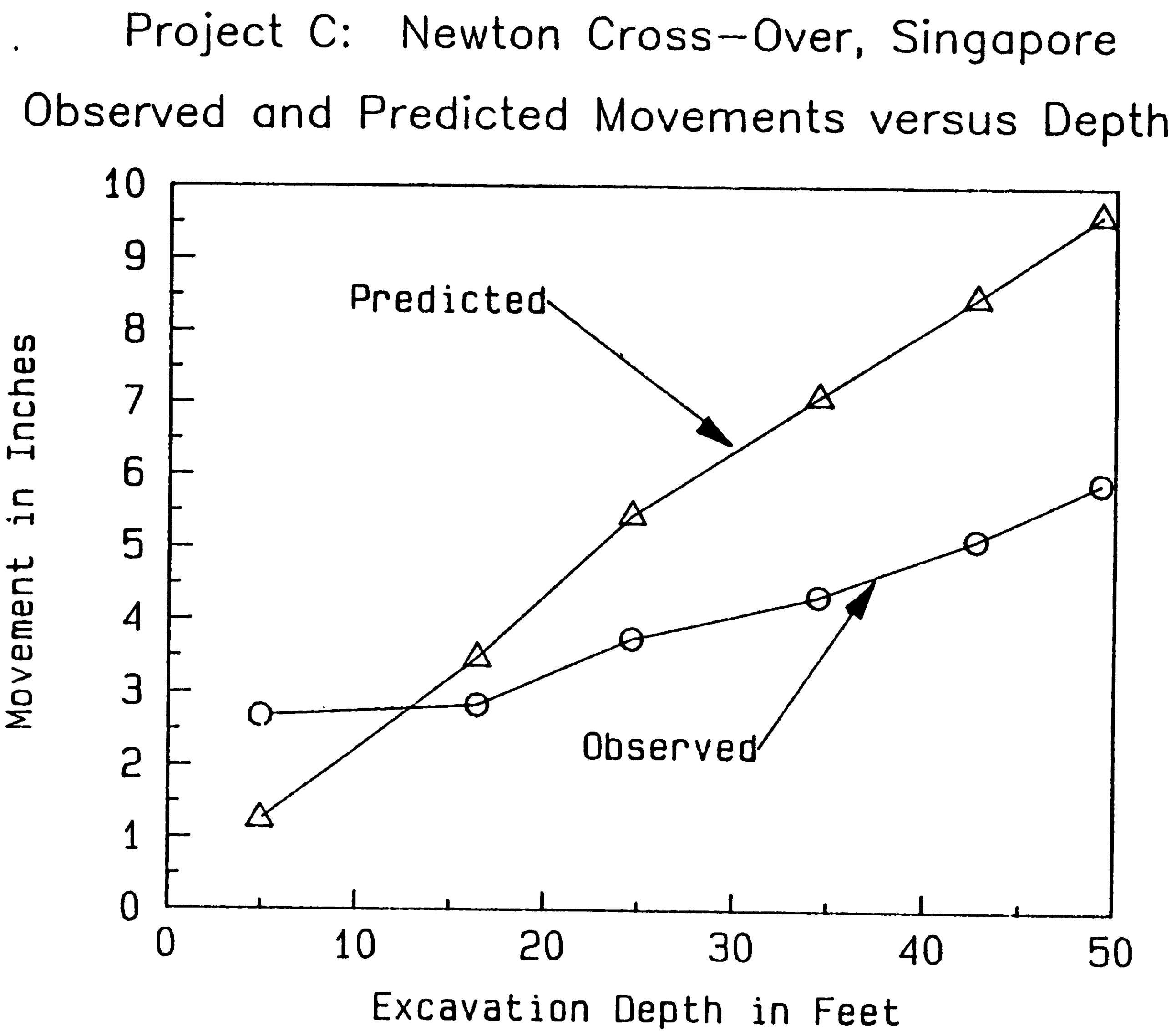



Figure 6.6 - MOVEX Predictions for Case C

C.11 and C.12). For both Su(low) and Su(high) cases, the FS is at or below 1 at stage 2 and beyond. Broms, et al (1986) do not mention any failure for this case, and the author assumes failure did not occur. The variability of the soil profile across the site probably caused the factor of safety to be higher than that calculated by MOVEX for the most critical soil profile.

Measurements of actual surface settlement adjacent to Case C are provided in Broms, et al (1986). The measured settlements provided are 0.1m (4 inches) at approximately 10m (33 feet) from the excavation, and 0.07m (2.7 inches) adjacent to the wall. The maximum settlement predicted by MOVEX is 0.22m (8.7 inches) adjacent to the wall. Thus the predicted settlements are conservative for this case.

6.3.4 Newton Station, Case D

The Newton Station project is a 13.3m deep excavation with a width of 21.2m. The support system is of slurry wall construction. The available data are provided in Table 6.11, with the shear strength values given in Table 6.12. The top two struts model a 2m thick roof slab which spans the width of the excavation; the top strut represents the top of the roof slab, and the second strut represents the bottom of the roof slab. The third strut models a concourse. The length of the excavation was not given by

Wong (1987), and was assumed to be a large value (100m) because subway stations are generally long.

The observed and predicted wall movements are shown in Figure 6.7. Only the final maximum observed movement is plotted because the movements at the various excavation stages were not available. However, the cantilever movement was shown on the final wall profile, and was used in the MOVEX predictions. The initial cantilever movements of about 2.5 inches cause the large movements shown for stage 1 of the MOVEX predictions. The predicted displacements at the next two excavation stages increase and then decrease. The FS drops below 1 for the $S_u$(low) case at stage 2, but the influence of the firm sand layer at 14m causes the FS to increase between stages 2 and 3. The same happens in the $S_u$(high) case, except the FS does not drop below 1. The actual factors which causes the wall movements to decrease at the final excavation stage are the alpha factors described in Chapter 2, which take into account the presence of a firm layer below the excavation bottom, the depth of the excavation versus its width, and the strut stiffness and spacing. These values are provided in Tables C.13 and C.14 of Appendix C.

The MOVEX predicted movements for Case D are about 1 to 2 inches larger than the observed movement. The database upon which MOVEX is based had limited data from

Table 6.11

Values used to Evaluate Case D

| Parameter | Symbol | Value |
|---|---|---|
| Fill Layer (0-3m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 17 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 0+2.3h |
| | $S_u$(high) | 30 |
| Upper Marine Clay Layer (3-13m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 16 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 6.9+1.4h |
| | $S_u$(high) | 15+0.6h |
| Sand Layer (13-14m) | | |
| Total Unit Weight (kPa/m) | $\gamma$ | 19 |
| Undrained Shear Strength (kPa) | $S_u$(low) | 20.5+2h |
| | $S_u$(high) | 30 |
| Wall Stiffness (kPa/m) | EI | $1.2 \times 10^6$ |
| Strut Stiffness (kPa/m) | | |
| Strut 1 (at 0m) | AE/L | $1.19 \times 10^6$ |
| Strut 2 (at 2m) | AE/L | $1.19 \times 10^6$ |
| Strut 3 (at 7m) | AE/L | $4.62 \times 10^5$ |
| Excavation Width (m) | B | 21.2 |
| Excavation Length (m) | L | 100 |
| Final Excavation Depth (m) | D | 13.3 |
| Depth to Firm Layer (m) | | 14 |
| Surcharge Next to Excavation (kPa) | q | 0 |
| Cantilever Movement Top of Wall (m) | CEM | 0.06 |
| Cantilever Hinge Depth (m) | CEH | 16 |
| Unit Weight of Water (kPa/m) | $\gamma_w$ | 9.81 |

Table 6.12

Evaluation of Shear Strength Ranges for Case D

| Layer | Depth | $\gamma$ | $S_u$ | $\sigma_v'$ | $S_u$(low) |
|---|---|---|---|---|---|
| Fill | 0<br>3 | 17 | 30 | -<br>31.4 | 0<br>6.9 |
| Upper Marine Clay | 3<br>13 | 16 | 15 | 31.4<br>93.3 | 6.9<br>20.5 |
| Lower Clay | 13<br>14 | 19 | 30 | 93.3<br>102.5 | 20.5<br>22.5 |
| Lower Sand | FIRM LAYER | | | | |

| Layer | $S_u$(low) | $S_u$(avg) | $S_u$(high) |
|---|---|---|---|
| Fill | 0 + 2.3h | 30 | 30 |
| Upper Clay | 6.9 + 1.4h | 15 | 15 + 0.6h |
| Lower Clay | 20.5 + 2h | 30 | 30 |

$S_u$(low) = (0.22) $\sigma_v'$
$S_u$(avg) is the average given in Broms, et al (1986)
$S_u$(high) is the higher of $S_u$(low) and $S_u$(high) with depth
Water Table is at 1m depth, and $\gamma_w$ = 9.81 kPa/m

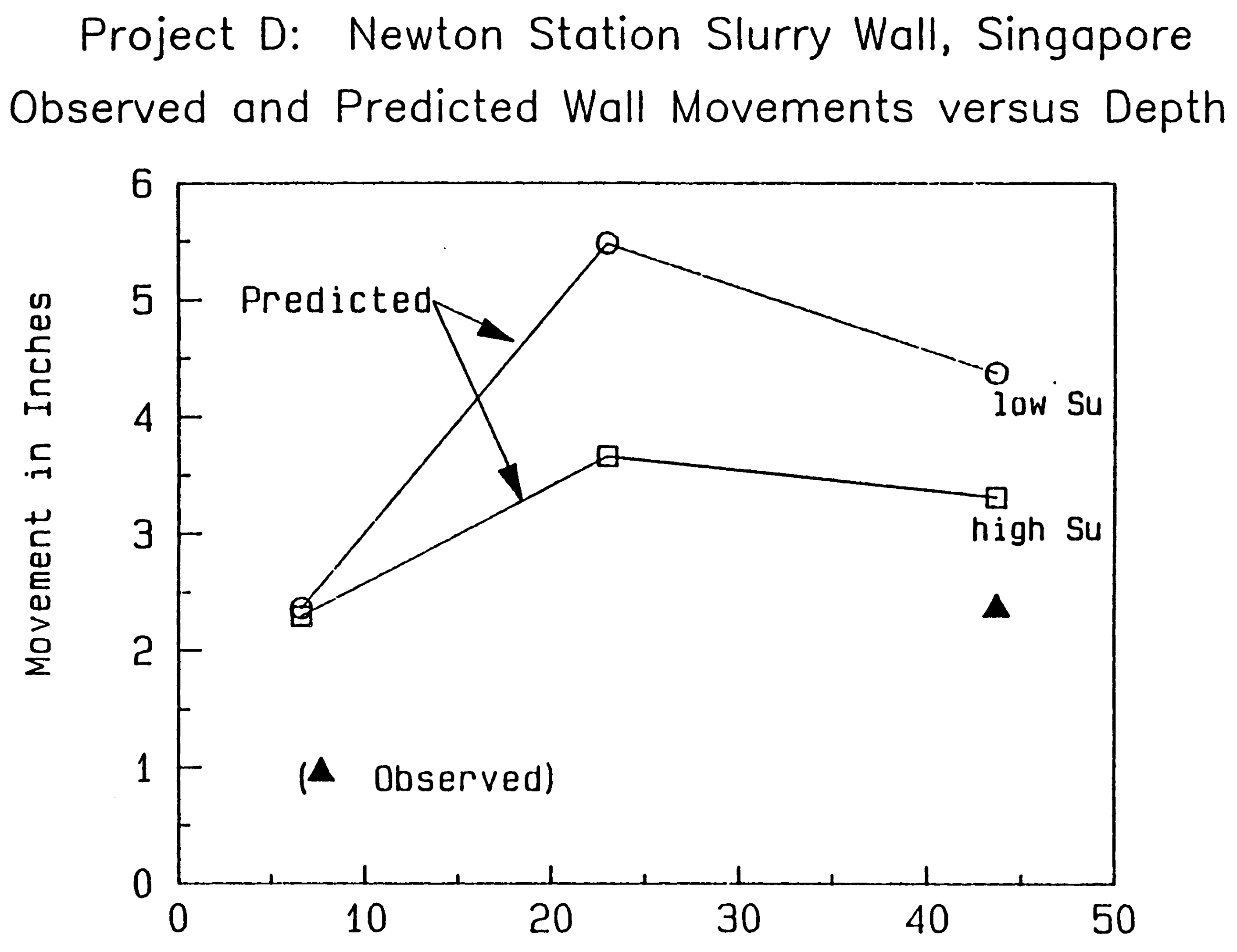



Figure 6.7 - MOVEX Predictions for Case D

slurry wall construction, and this limitation may be the cause of the discrepancies between observed and predicted movements. Other causes could be variation of actual shear strengths and soil profiles across the site.

## 6.4 Summary of Case Histories

Figure 6.8 shows the results of the trends of MOVEX predicted movements versus the observed movements for the seven case histories presented in this chapter. Both high and low strength predictions (unless the results were equal for both cases) were plotted versus the observed movements. In cases where more than one set of movement data were available, both MOVEX predictions were plotted against each set of movement data (ie., if there were two sets of inclinometer data for one excavation). Thus, there are more than one set of points plotted for each case history. The results of the MOVEX predictions form an approximately 52-degree angle, which indicates a trend of relative conservative accuracy of the predicted movements.

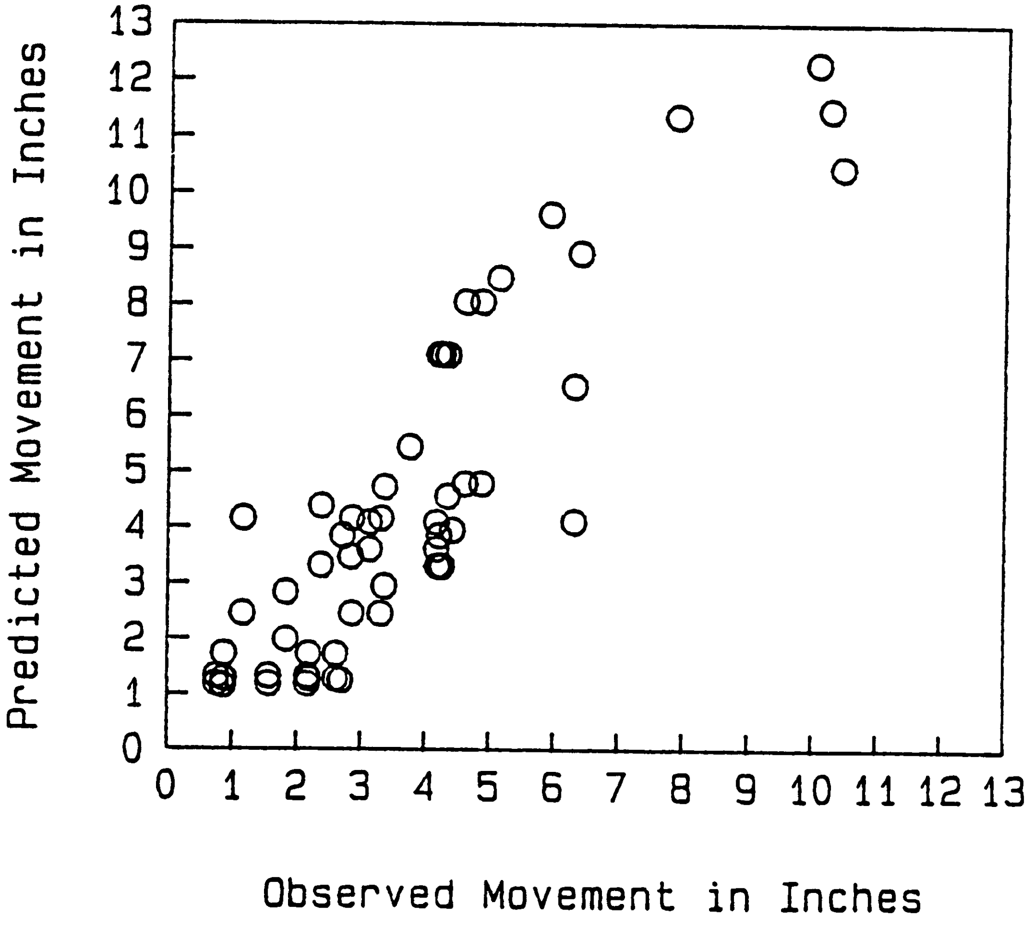



Figure 6.8: MOVEX Predictions of Lateral Wall Movements versus Observed Wall Movements for Seven Case Histories

# Chapter 7

## Summary and Conclusions

The main objective of this thesis is to provide an easy to use, reasonable method to predict wall and ground surface movements of supported excavations in clays. The personal computer program MOVEX is designed to meet this criterion. The methods used by MOVEX are based upon finite element analyses and field data. MOVEX accounts for several of the variables important to braced excavation behavior, including strut and wall stiffness, strut spacing, soil strengths and layer thicknesses, soil anisotropy, cantilever movements, excavation depth and geometry, and surcharge loads above the excavation. This program was developed originally in 1981 and has been gradually improved over the past several years. This work represents a further step in this process.

The improvements incorporated in this effort include insuring the proper operation of the program, revising the printed output, and adding features to allow for effects of anisotropy in the soil strength, and wall movements due to the initial cantilever stage. A number of case histories and example problems were evaluated with MOVEX to check the program operation, and to provide data for future users of the program.

Several conclusions can be drawn from this research:

1. Wall movements are dominated by the FS and the system stiffness unless cantilever movements are allowed to become so large that they control the movement pattern.

2. The shear strength is often difficult to define accurately, and in the case of low factors of safety against basal heave, small differences in shear strength lend to large differences in predicted movements.

3. The system stiffness is sensitive to strut spacing. Large distances between the struts allow the system to become flexible and increase wall movements and wall bending moments.

4. Construction procedure and workmanship can substantially influence wall movements; late installation of struts and inadequate or improper preloading techniques can cause wall movements to increase.

5. The depth to a firm soil layer influences the FS calculation, which in turn influences the movement pattern of a supported wall.

All of these factors are demonstrated in the case histories and example problems given in this thesis.

Supported excavations are unique, and no two excavation systems behave exactly alike. The general intent of the designer should be to arrive at a reasonable estimate of wall movements which bound likely actual behavior. This philosophy is the same as that used in design of foundations bearing on sandy soils. MOVEX provides a tool to accomplish this objective for excavations in clayey soils.

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# Appendix A

# MOVEX User's Guide

Introduction

The program MOVEX computes the ground movements around braced excavations. It has several useful features:

- Any combination of horizontal soil layers, excavation geometries and stiffnesses can be used.
- Several design options are available for the convenience of the user.
- The factor of safety shown for each stage is the minimum value at any point in excavating between stages.
- The distribution of lateral and vertical ground movements at various distances from the excavation are calculated.
- The program includes an interactive design section in order to quickly arrive at the optimal combination of strut and wall stiffnesses to control movement.
- The program allows for the anticipation of cantilever wall movements.
- The program can allow for soil anisotropy effects.

The program is based on the design method by Mana and Clough (1981). The first version of MOVEX was developed by Sunami (1981). Modifications were made by Goessling (1985), and later by Smith (1986). Further modifications and corrections were made by Smith (1987) under the direction of Professor G. W. Clough at Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

## System Requirements

This program has been written to run under MS-DOS. Hardware requirements include 64 to 128 kilobytes of RAM memory and at least 1 floppy disk drive. It is not necessary for the user to have a copy of the FORTRAN compiler in order to execute this program; however, it would be necessary if modifications were made to the program.

The accompanying diskette contains the following files:

Source Files
Executable File
Data File for Example
Output File for Example

The files were compiled on the MS-DOS operating system using the Microsoft FORTRAN version 3.3 compiler.

The user should make a backup copy of the program diskette and store the original. It is not necessary to copy the source files if the program is not going to be changed.

## Program Operation

The program consists of a main section, MOVEX, and several subroutines: FSHEAV, DSTRB, SDISP, CHNG, COEFS, DECOMP, and SOLVE. Their functions are briefly explained below.

MOVEX is the main segment of the program. It reads all the input, and for each excavation stage, calls the subroutines FSHEAV, DSTRB, and SDISP. It also controls the overall execution of the program.

FSHEAV calculates the factor of safety against basal heave.

DSTRB calculates the distribution of lateral and vertical ground movements for various distances from the wall.

SDISP finds the lateral wall displacement, evaluates the cantilever movement, and finds the terms $\alpha_S$, $\alpha_B$, and $\alpha_D$.

CHNG controls the interactive change section.

COEFS, DECOMP, and SOLVE are curve-fitting subroutines.

Program Execution

Prior to running the program, it is necessary to create a data file using a text editor or a word processor. For a single-disk system, the data file should be saved on the program disk. For dual-disk systems, the data file can be saved either on the program disk, or on a separate data disk.

Once the data file has been created, and the system prompt ( >A) appears, simply type MOVEX followed by a return, and the program will begin. A title page like the one shown below will appear on the screen. Input the name of the data file, and select the output destination.

```
***************************************
*                                     *
*               MOVEX                 *
*                                     *
*     A program for the design of     *
* excavation bracing to limit lateral *
*      ground movements in clays.     *
*                                     *
***************************************

        NAME OF INPUT FILE:
         (e.g. B:xyz.dat) -->

        OUTPUT DESTINATION:

             0 = SCREEN
             1 = PRINTER
             2 = DISK

        PLEASE SPECIFY -->
```

Assumptions Used in Creating MOVEX

The following is a listing of the basic assumptions with which the MOVEX program was developed.

(1) MOVEX calculates wall and surface movements based on prompt installation of the first strut level. The depth of excavation prior to installation of the first strut level should not exceed the depth d defined by

$d = 2c/\gamma$ where c = the cohesion of the first soil layer (force/length$^2$), and $\gamma$ = the unit weight of the first soil layer (force/length$^3$). If this is not true, cantilever wall movements can be significant.

(2) The design procedure assumes minimum excavation takes place below strut levels prior to strut installation.

(3) The strut spacing is assumed to be regular in that relatively uniform spacing of strut levels is used. The program cannot properly evaluate excavations in which strut spacings vary widely, such as 15 ft. spacing between levels 1 and 2, and 5 ft. spacing between levels 2 and 3.

(4) The depth to firm soil is checked by the program user for the soil layer which causes the minimum factor of safety against basal heave. The depths which should be checked are the depths to the base of each relatively firm soil layer at or below the excavation bottom. When a firm layer is at or below the base of the excavation, the FS will first decrease with depth, and then increase once the effect of the firm layer is felt. Since the minimum FS occurs just before the influence of the firm layer is felt, this is the value which governs supported wall system displacements.

Description of Input for MOVEX

It is not necessary to type the input data in formatted columns. The numbers can be typed one after another separated by one or more commas. Decimal points need only be typed for numbers having fractional parts, such as 5.32 or 0.08. Blanks are not interpreted as zeros.

Zeros must be typed. Any system of units (SI, English, etc.) may be used, but units must be consistent. Units are shown in the manual in square brackets [ ], using the following notation (or a combination thereof):

[L] = length
[F] = force

A: PROBLEM IDENTIFICATION

TITLE - (maximum or 72 characters), any desired identifying information.

B. SYSTEM OF UNITS

'UNIT', 'LENG', 'FORC', where:

'UNIT' = the system of units used, ie, 'English', 'SI', etc. (MUST BE ENCLOSED IN APOSTROPHES).

'LENG' = the units of length used, ie, 'feet', 'meters', etc. (MUST BE ENCLOSED IN APOSTROPHES).

'FORC' = the units of stress used, ie, 'pounds per square foot', 'kilopascals', etc. (MUST BE ENCLOSED IN APOSTROPHES).

C. USER OPTIONS

MOPT, NOPT, where:

MOPT = movement distribution option:

MOPT = 0 : vertical and lateral distribution of movement with respect to distance from wall calculated.

MOPT = 1 : movement distribution not calculated.

NOPT = design option:

NOPT = 0 : entire excavation geometry and stiffness is input; maximum lateral wall movement calculated for each excavation stage.

NOPT = 1 : excavation geometry and maximum allowable lateral wall movement input; wall stiffness (EI) is calculated.

NOPT = 2 : excavation geometry and stiffness, and maximum allowable lateral wall movement input; required strut spacing calculated.

NOPT = 3 : excavation geometry and maximum allowable lateral wall movement input; required strut stiffness calculated.

D. CONTROL DATA

NLAY, NSTRT, XKS, where:

NLAY - total number of soil layers in the vicinity of the excavation. Include layers that extend either to a firm layer below the excavation bottom, or to a distance of twice the final excavation height below the bottom of the excavation. Maximum of twenty (20) soil layers.

NSTRT - total number of struts in the excavation. Maximum of ten (10) struts (or tiebacks).

XKS - anisotropic strength ratio. Use XKS = 1.0 if soil is isotropic.

E. CANTILEVER EFFECT DATA

CE, CEM, CEH, where:

CE = Cantilever Effect:

CE = 0 : no cantilever movements anticipated.

CE = 1 : cantilever movements are anticipated.

CEM = Cantilever movement at the top of the wall [L].

{CEM = 0 if CE = 0}

CEH = Depth to hinge point [L].

{CEH = 0 if CE = 0}

F. SOIL DATA - One line for each soil layer. There should be NLAY lines.

J, H, GT, CO, DC, where:

J = layer number, starting with the topmost layer as number 1 [L].

H = thickness of layer J [L].

GT = total unit weight of the soil in layer J $[F/L^3]$.

CO = undrained shear strength (cohesion) at the top of the clay layer $[F/L^2]$.

DC = change in undrained shear strength with depth per unit depth of the clay layer $[F/L^2$ per L].

G. FIRM LAYER DATA

DF, where:

DF = depth to a firm layer from the ground surface [L]. For a very deep clay layer, input any number greater than (H + 0.7B) where H = final excavation depth [L], and B = total excavation width [L].

For layered soil systems, run the program several times, varying DF. Values of DF in this case should be equal to the depth to the bottom of each firm soil layer below the base of the excavation. The value of DF which results in the lowest FS and the largest system movements should be considered the actual DF for design.

H. WATER TABLE DATA

GW, where:

GW = unit weight of water $[F/L^3]$.

I. EXCAVATION GEOMETRY (see Figure A.1)

B,ELN,HW,Q, where:

B = total excavation width [L].

ELN = total excavation length [L].

HW = final excavation depth [L].

Q = surcharge next to the excavation [$F/L^2$].

STRUT-WALL-DEFLECTION DATA - Choose the appropriate input, based on the value of NOPT.

For NOPT = 0 (find maximum displacement),

J. Wall Stiffness

EI, where:

EI = bending stiffness of the wall [F $L^2$ per unit length of wall], where E = modulus of the wall material [$F/L^2$], and I = moment of inertia per unit length of wall [$L^4$ per unit L].

K. STRUT DATA

J, HS, S, where:

J = strut number, starting with topmost strut as number 1.

HS = strut spacing [L], distance between strut J and the strut above it. For the top strut, HS is the distance between the strut and the ground surface.

S = strut stiffness [F/L per unit length of wall].
- AE/L per unit length of wall, where:
A = cross-sectional area off the strut [$L^2$]
E = modulus of the strut material [$F/L^2$]
L = effective length of the strut [L].

For NOPT = 1 (find wall stiffness)

J. DISPLACEMENT DATA

DLM, where:

DLM = maximum allowable lateral movement of the wall [L].

K. STRUT DATA - One line for each strut; there should be NSTRT line(s) of data.

J, HS, S, where:

J = strut number, starting with topmost strut as number 1.

HS = strut spacing [L], distance between strut J and the strut above it. For the top strut, HS is the distance between the strut and the ground surface.

S = strut stiffness [F/L per unit length of wall].
- AE/L per unit length of wall, where:
A = cross-sectional area off the strut [$L^2$]
E = modulus of the strut material [$F/L^2$]
L = effective length of the strut [L].

For NOPT = 2 (find average strut spacing)

J. DISPLACEMENT DATA

DLM, where:

DLM = maximum allowable lateral movement of the wall [L].

K. Wall Stiffness

EI, where:

EI = bending stiffness of the wall [F $L^2$ per unit length of wall], where E = modulus of the wall material [$F/L^2$], and I = moment of inertia per unit length of wall [$L^4$ per unit L].

L. AVERAGE STRUT STIFFNESS

SAVG, where:

SAVG = AE/L per unit length of wall [F/L per unit length of wall], where A = cross-sectional area of the struts [$L^2$], E = average modului of the strut materials [$F/L^2$], and L = effective strut length [L].

For NOPT = 3 (find strut stiffness)

J. DISPLACEMENT DATA

DLM, where:

DLM = maximum allowable lateral movement of the wall [L].

K. Wall Stiffness

EI, where:

EI = bending stiffness of the wall [F $L^2$ per unit length of wall], where E = modulus of the wall material [$F/L^2$], and I = moment of inertia per unit length of wall [$L^4$ per unit L].

L. STRUT SPACING - One line for each strut; there should be NSTRT line(s) of data.

J, HS, where:

J = strut number, starting with topmost strut as number 1.

HS = strut spacing [L], distance between strut J and the strut above it. For the top strut, HS is the distance between the strut and the ground surface.

Interactive Design

After the program has been run with the original data file, the user is given three options: make changes to the design, run a new program, or exit to DOS. If the first option is selected, changes can be made to the original data file by responding to prompts from the screen as follows.

The user inputs a new input data file name. The name can either be the same as the original file, in which case all original data will be overwritten, or the name can be different from the original name, in which case a totally new file will be created. In either case, the program will automatically run using the new data file. Any part of the data file can be changed except the title (item A - Problem Identification) and the system of units (item B - System of Units). If NOPT is changed, all of the data required for the new value of NOPT must be entered. This information is summarized in Table A.1.

The program will prompt for the necessary information in the manner shown below:

Change User Options? (yes/no)

Change anisotropic strength ratio? (yes/no)

Change cantilever effect data? (yes/no)

Change soil parameters? (yes/no)

This is not a complete listing of the information provided with the CHANGE option. Interested readers are referred to the program itself or to the program listing for the complete routine.

Table A.1

DATA REQUIRED WHEN NOPT IS CHANGED INTERACTIVELY IN MOVEX

| | NEW NOPT | | | |
|---|---|---|---|---|
| OLD NOPT | 0 | 1 | 2 | 3 |
| 0 | --- | DLM<br>SAVG | DLM | DLM |
| 1 | EI | --- | SAVG | EI |
| 2 | EI<br>J,HS,S | J,HS,S | --- | EI<br>J,HS |
| 3 | J,HS,S | J,HS,S | SAVG | --- |

For further information on each variable given for each value of NOPT, see Description of Input for MOVEX section.

Description of Output From MOVEX

In the computer output, the first major items: title, unit system, cantilever effect data, soil layer data, water table data, excavation geometry, and strut data are values that were read from the data file. The format of these data remains virtually the same, regardless of the values of MOPT or NOPT. The calculated output, however, depends on the design options specified. The output for the example in Appendix B is shown in Table B-1.

If MOPT = 0 (calculate the distribution of movements), both the vertical and lateral displacements (in units of length) are calculated at various distances from the wall (length).

The input and output for each design option (NOPT) is summarized in Table A.2. The maximum lateral wall movements are given in units of length, the required wall stiffness, EI, in units of Force-length$^2$ per unit length of wall, the required strut stiffness in force/length per unit length of wall, and the required strut pacing (in the vertical direction) in units of length.

Suggestions for the Use of MOVEX for Design

The design of the support system for a braced excavation consists of two major requirements: stiffness

Table A.2

Input and Output Options for MOVEX

| NOPT | INPUT | OUTPUT |
|---|---|---|
| 0 | wall stiffness<br>strut stiffness<br>strut spacing | FS at each stage<br>maximum lateral wall movement<br>minimum FS |
| 1 | maximum allowable lateral wall movement<br>strut spacing<br>strut stiffness | FS at each stage<br>required wall stiffness<br>minimum FS |
| 2 | maximum allowable lateral wall movement<br>wall stiffness<br>average strut stiffness | minimum FS<br>required strut spacing |
| 3 | maximum allowable lateral wall movement<br>wall stiffness<br>strut spacing | FS at each stage<br>required average strut stiffness<br>minimum FS |

and stability of the wall and struts. Other variables to consider are the horizontal and vertical strut spacing, the spacing of intermediate stiffeners within the excavation, the depth to a firm soil layer, soil strength parameters, the maximum allowable ground movement, etc. If none of these variables are known, the problem of designing an excavation "from scratch" is a complicated process.

The following guidelines are given to help in the efficient design of the excavation bracing using MOVEX. The general idea is to set all but one of the variables, then run the program to find the missing parameter. Once a structural section is selected from this parameter, the program is run again to determine its influence on the other variables.

(1) Calculate (by hand) the maximum bending moment in the wall and the strut loads based on earth pressure theory.

(2) Select a bracing design based on the values calculated in Step 1.

(3) With NOPT = 0, run MOVEX to determine the wall and ground movements associated with the bracing design.

(4) If the wall movement exceeds the maximum allowable wall displacement, run the program again with NOPT = 1 or 2 to determine the appropriate wall and strut stiffnesses required to limit ground movement.

(5) If any of the sections (strut or wall) seem excessively large or small, try changing the strut spacing to compensate. Note that small changes in the strut spacing have a large influence on the other variables.

Suggestions for the use of MOVEX for Movement Predictions

(1) Evaluate the wall movements based on a range of reasonable values of undrained shear strength for each soil layer. This will provide a range of movements to be expected.

(2) Using the interactive design option, vary the depth to firm layer (DF). This will check for the minimum factor of safety against basal heave. The depths which should be checked are the depths to the base of each soil layer at or below the excavation bottom.

# Appendix B

## Updated Example Problem: Islais Creek

(After Goessling,1985)

**EXAMPLE**: Compare MOVEX calculations with field measurements of movements of a braced excavation. Case history is from "Measured Behavior of Braced Wall in Very Soft Clay," (Clough and Reed, 1984). Soil conditions are shown in Figure B - 1. Excavation is shown in Figure B - 2. Calculate the wall movements associated with the braced excavation construction.

**SECTION PROPERTIES**:

sheet pile PZ 32 $E = 4.2 \times 10^9$ psf

$I = 382\ in^4$ per pile
$= 220.6\ in^4$ per foot wall

$$EI = 4.2 \times 10^9 \cdot 0.011\ ft^4/ft \text{ wall}$$
$$= 4.5 \times 10^7\ lb \cdot ft^2/ft$$

steel struts HP 12x74 $E = 4.2 \times 10^9$ psf

$A = 21.8\ in^2 = 0.15\ ft^2$
$L = 25$ ft

$$K_I = \frac{0.15 \cdot 4.2 \times 10^9}{25 \cdot 15} = 1.7 \times 10^6 \frac{lb/ft}{ft \text{ wall}}$$

wood strut $E = 2.5 \times 10^8$

$A = 1\ ft^2$
$L = 25$ ft

$$K_I = \frac{1 \cdot 2.5 \times 10^8}{25 \cdot 15} = 6.7 \times 10^5 \frac{lb/ft}{ft \text{ wall}}$$

MOVEX input shown in Table B - 1. Computer output shown in Table B - 2. Measured wall movements are shown in Figure B - 3.

Table B-1

MOVEX Input File for Example Problem

```
Islais Creek Excavation including fill, 3 struts
'English'     'Feet'   'PSF'
1             0
3             3         1
0             0         0
1      10.0        110.0           .00           .00
2      20.0         91.0        350.00           .00
3      70.0         96.0        450.00           .00
100
62.4
25   500          30    0
45000000
1     0      670000
2     14     1700000
3     10     1700000
```

Table B-2

PROGRAM MOVEX

Islais Creek Excavation including fill, 3 struts

The system of units used is English
The units of length are - Feet
The units of stress are - PSF

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

No Cantilever Movements are Anticipated

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 10.00 | Cohesion | .00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 350.00 |
| Unit Weight | 91.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 70.00 | Cohesion | 450.00 |
| Unit Weight | 96.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 100.000

WATER TABLE DATA

Unit weight of water 62.40

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 25.00 |
| Total length of excavation | 500.00 |
| Final depth of excavation | 30.00 |
| Surcharge next to excavation | .00 |

Wall Stiffness (EI) .450E+08

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | .00 | .6700E+06 |
| 2 | 14.00 | .1700E+07 |
| 3 | 24.00 | .1700E+07 |

MOVEMENT CALCULATIONS

Average Strut Spacing = 10.00
Nondimensional System Stiffness = 72.12

Excavation stage 2

Height of excavation is 14.000
Factor of safety against basal heave is 1.3084
Minimum factor of safety between stages is 1.3084

Average Strut Stiffness = 1185000.00
Alpha D = 1.00
Alpha B = 1.23
Alpha S = .74

Lateral Wall Movement at this Stage is .121
Overall Maximum Lateral Wall Movement is .121

Excavation stage 3

Height of excavation is 24.000
Factor of safety against basal heave is 1.0026
Minimum factor of safety between stages is 1.0026

Average Strut Stiffness = 1356667.00
Alpha D = 1.00
Alpha B = 1.05
Alpha S = .75

Lateral Wall Movement at this Stage is .364
Overall Maximum Lateral Wall Movement is .364

Excavation stage 4

Height of excavation is 30.000
Factor of safety against basal heave is .9018
Minimum factor of safety between stages is .9018

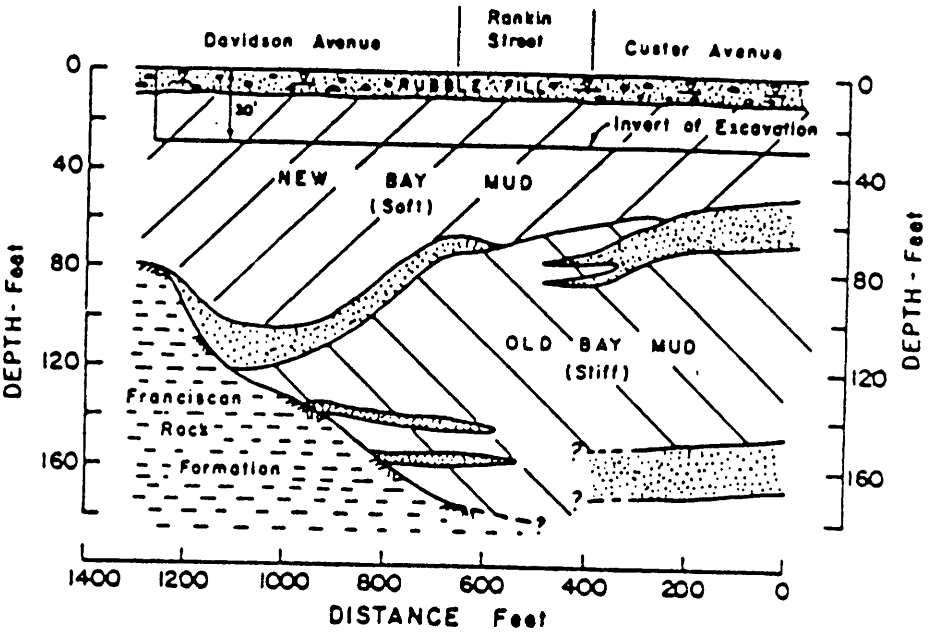
**CAUTION: Factor of safety is less than 1.0**

Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 1363200.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.01 |
| Alpha S = | .76 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .655 |
| Overall Maximum Lateral Wall Movement is | .655 |




**—Soil Profile along Culvert Axis (1 ft = 0.305 m)**

**—Comparison of Properties of Bay Mud from Custer Avenue and Rankin Street and Davidson Avenue**

| Depth, in feet (meters) | Average Water Content, as a Percentage | | Average Unit Weight, in Pounds per Cubic Foot (Kilograms per Cubic Meter) | | Average Shear Strength, in Pounds per Square Foot (Pascals) | | OCR[c] | | Sensitivity | | *PI*, as a Percentage | | LL, as a Percentage | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D[a] | C[b] | D | C | D | C | D[d] | C | D | C | D | C | D | C |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) |
| 0–30 (0–9) | 95 | 92 | 91 (1,460) | 92 (1,470) | 350 (16,770) | 500 (24,000) | 1.4 | 1.5 | 15 | 10 | 59 | 59 | 105 | 95 |
| 30–55 (9–17) | 75 | 65 | 96 (1,540) | 104 (1,670) | 450 (21,600) | 800 (38,300) | 1.0 | 1.5 | 10 | 10 | 45 | 38 | 85 | 68 |

[a]D = Davidson Avenue.
[b]C = Custer Avenue and Rankin Street.
[c]OCR = overconsolidation ratio.
[d]Based on effective pressures with allowances for artesian pressure.
Note: 1 psf = 47.9 N/m$^2$; 1 pcf = 0.157 kN/m$^3$.

FIGURE B.1 - Example Problem - Soil Data

(from Clough and Reed, 1984)

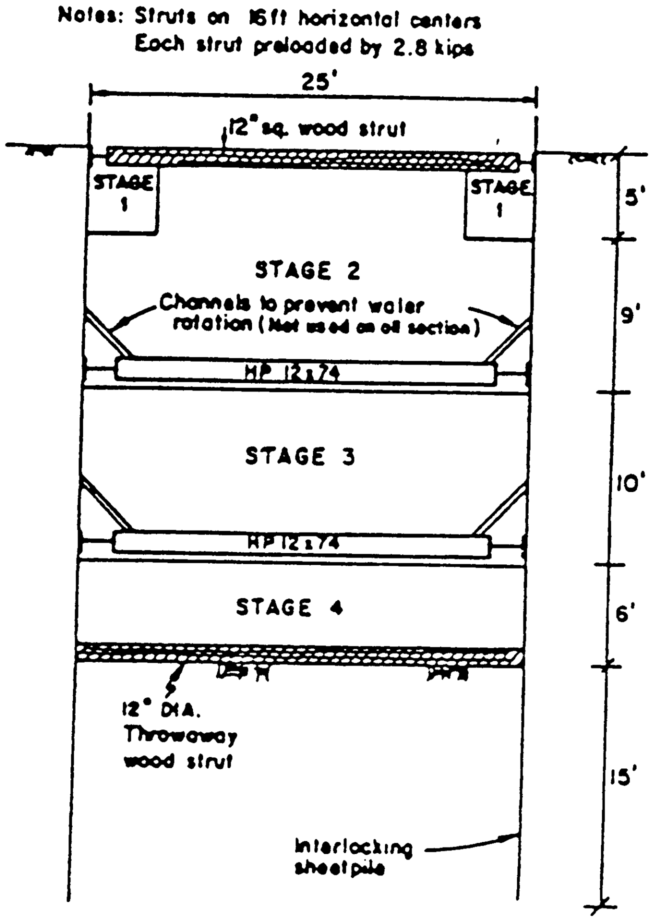



FIGURE B.2 - Example Problem - Strut Geometry

(from Clough and Reed, 1984)

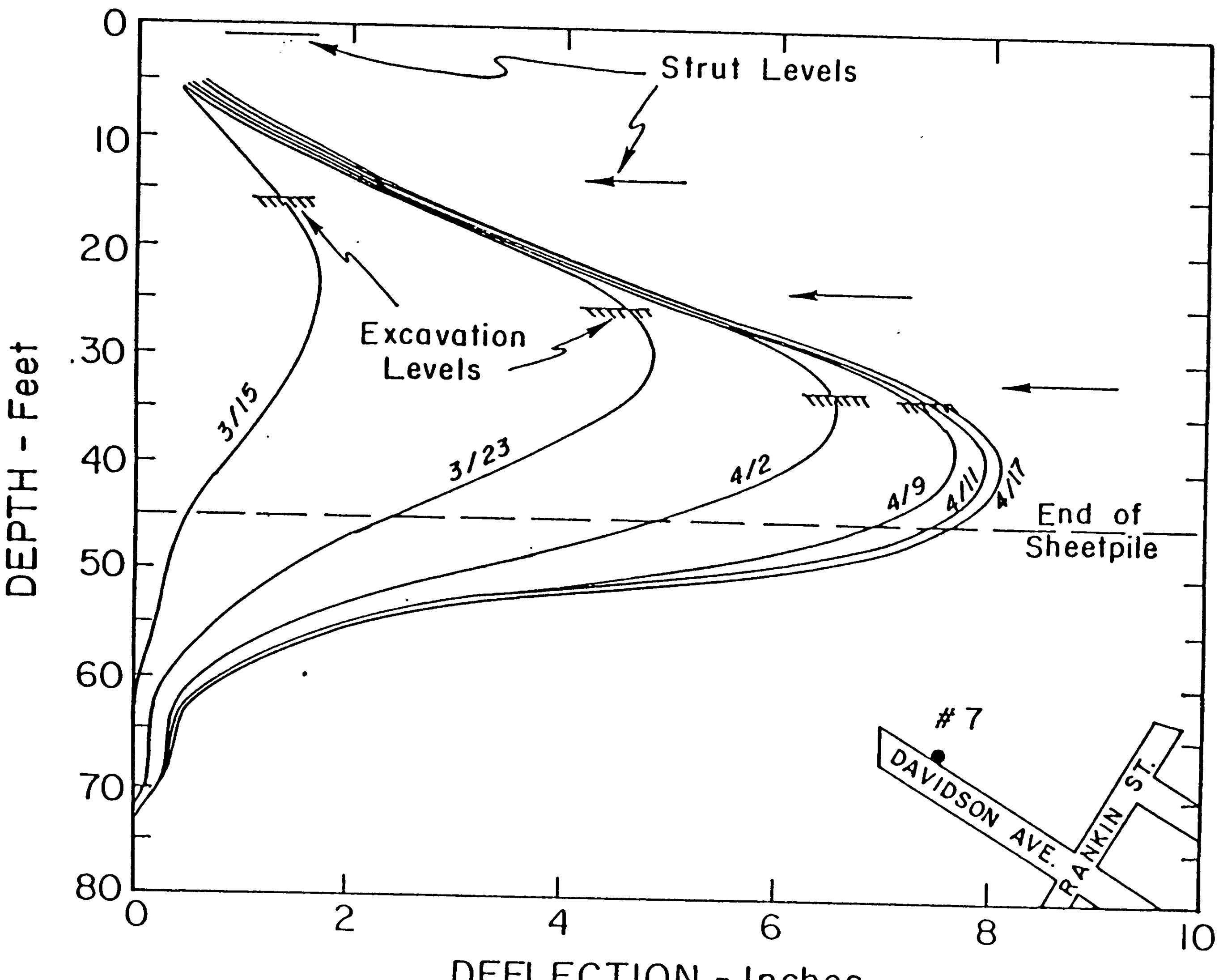



FIGURE B.3 - Example Problem - Measured Movements

(from Clough and Reed, 1984)

Appendix C

MOVEX Output for Case History Problems

Table C.1

MOVEX Output for Case 1, High Strength

PROGRAM MOVEX

ONE FINANCIAL PLACE, CHICAGO, C NOT = 0 FOR GRANULAR SOILS

The system of units used is English
The units of length are - Feet
The units of stress are - PSF

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 4 |
| Number of struts | 2 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .083 |
| Anticipated Hinge Depth = | 50.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 5.00 | Cohesion | .00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 5.00 | Cohesion | 800.00 |
| Unit Weight | 90.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 49.00 | Cohesion | 900.00 |
| Unit Weight | 120.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 13.00 | Cohesion | 6000.00 |
| Unit Weight | 120.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 59.000

WATER TABLE DATA

| | |
|---|---|
| Unit weight of water | 62.40 |

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 185.00 |
| Total length of excavation | 150.00 |
| Final depth of excavation | 30.00 |
| Surcharge next to excavation | 100.00 |
| Wall Stiffness (EI) | .380E+08 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 9.00 | .6480E+06 |
| 2 | 23.00 | .8080E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 10.50 |
| Nondimensional System Stiffness = | 50.10 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 9.000 |
| Factor of safety against basal heave is | 5.4824 |
| Minimum factor of safety between stages is | 5.4824 |

| | |
|---|---|
| Average Strut Stiffness = | 648000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .74 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .028 |
| Cantilever Movement at this Stage is | .068 |
| Total Wall Movement at this Stage is | .096 |
| Overall Maximum Lateral Wall Movement is | .096 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0965 | .0347 |
| 4.50 | .0965 | .0695 |
| 9.00 | .0917 | .0888 |
| 13.50 | .0724 | .0946 |
| 18.00 | .0579 | .0907 |
| 22.50 | .0434 | .0791 |
| 27.00 | .0289 | .0627 |
| 31.50 | .0241 | .0482 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 23.000 |
| Factor of safety against basal heave is | 2.4403 |
| Minimum factor of safety between stages is | 2.4403 |

| | |
|---|---|
| Average Strut Stiffness = | 728000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .79 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .120 |
| Cantilever Movement at this Stage is | .045 |
| Total Wall Movement at this Stage is | .165 |
| Overall Maximum Lateral Wall Movement is | .165 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1652 | .0595 |
| 11.50 | .1652 | .1189 |
| 23.00 | .1569 | .1520 |
| 34.50 | .1239 | .1619 |
| 46.00 | .0991 | .1553 |
| 57.50 | .0743 | .1355 |
| 69.00 | .0496 | .1074 |
| 80.50 | .0413 | .0826 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 30.000 |
| Factor of safety against basal heave is | 1.9919 |
| Minimum factor of safety between stages is | 1.9919 |

| | |
|---|---|
| Average Strut Stiffness = | 728000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .82 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .211 |
| Cantilever Movement at this Stage is | .033 |
| Total Wall Movement at this Stage is | .245 |
| Overall Maximum Lateral Wall Movement is | .245 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2445 | .0438 |
| 15.00 | .2445 | .0988 |
| 30.00 | .2323 | .1522 |
| 45.00 | .1834 | .1551 |
| 60.00 | .1467 | .1182 |
| 75.00 | .1100 | .0852 |
| 90.00 | .0734 | .0642 |
| 105.00 | .0611 | .0453 |

## Table C.2

## MOVEX Output for Case 1, Low Strength

PROGRAM MOVEX

ONE FINANCIAL PLACE, CHICAGO, C NOT = 0 FOR GRANULAR SOILS

| | |
|---|---|
| The system of units used is | English |
| The units of length are - | Feet |
| The units of stress are - | PSF |

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 4 |
| Number of struts | 2 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .083 |
| Anticipated Hinge Depth = | 50.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 5.00 | Cohesion | .00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 5.00 | Cohesion | 600.00 |
| Unit Weight | 90.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 49.00 | Cohesion | 700.00 |
| Unit Weight | 120.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 13.00 | Cohesion | 6000.00 |
| Unit Weight | 120.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 59.000

WATER TABLE DATA

Unit weight of water 62.40

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 185.00 |
| Total length of excavation | 150.00 |
| Final depth of excavation | 30.00 |
| Surcharge next to excavation | 100.00 |
| Wall Stiffness (EI) | .380E+08 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 9.00 | .6480E+06 |
| 2 | 23.00 | .8080E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 10.50 |
| Nondimensional System Stiffness = | 50.10 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 9.000 |
| Factor of safety against basal heave is | 4.1956 |
| Minimum factor of safety between stages is | 4.1956 |

| | |
|---|---|
| Average Strut Stiffness = | 648000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .74 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .028 |
| Cantilever Movement at this Stage is | .068 |
| Total Wall Movement at this Stage is | .096 |
| Overall Maximum Lateral Wall Movement is | .096 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0965 | .0347 |
| 4.50 | .0965 | .0695 |
| 9.00 | .0917 | .0888 |
| 13.50 | .0724 | .0946 |
| 18.00 | .0579 | .0907 |
| 22.50 | .0434 | .0791 |
| 27.00 | .0289 | .0627 |
| 31.50 | .0241 | .0482 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 23.000 |
| Factor of safety against basal heave is | 1.8189 |
| Minimum factor of safety between stages is | 1.8189 |

| | |
|---|---|
| Average Strut Stiffness = | 728000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .79 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .192 |
| Cantilever Movement at this Stage is | .045 |
| Total Wall Movement at this Stage is | .236 |
| Overall Maximum Lateral Wall Movement is | .236 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2364 | .0383 |
| 11.50 | .2364 | .0866 |
| 23.00 | .2246 | .1300 |
| 34.50 | .1773 | .1213 |
| 46.00 | .1419 | .0914 |
| 57.50 | .1064 | .0644 |
| 69.00 | .0709 | .0449 |
| 80.50 | .0591 | .0290 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 30.000 |
| Factor of safety against basal heave is | 1.4599 |
| Minimum factor of safety between stages is | 1.4599 |

| | |
|---|---|
| Average Strut Stiffness = | 728000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .82 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .360 |
| Cantilever Movement at this Stage is | .033 |
| Total Wall Movement at this Stage is | .393 |
| Overall Maximum Lateral Wall Movement is | .393 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3928 | .0731 |
| 15.00 | .3928 | .1587 |
| 30.00 | .3748 | .2121 |
| 45.00 | .2891 | .1768 |
| 60.00 | .2247 | .1351 |
| 75.00 | .1665 | .0943 |
| 90.00 | .1115 | .0613 |
| 105.00 | .0932 | .0346 |

Table C.3

MOVEX Output for Case 2, High Strength

PROGRAM MOVEX

QUAKER TOWER PROJECT, CHICAGO ILLINOIS, CLARK STREET, WEST WALL

| | |
|---|---|
| The system of units used is | English |
| The units of length are - | Feet |
| The units of stress are - | PSF |

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .330 |
| Anticipated Hinge Depth = | 45.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 10.00 | Cohesion | .00 |
| Unit Weight | 120.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 38.50 | Cohesion | 800.00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 32.50 | Cohesion | 2000.00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 48.500

WATER TABLE DATA

Unit weight of water 62.40

## EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 120.00 |
| Total length of excavation | 210.00 |
| Final depth of excavation | 32.50 |
| Surcharge next to excavation | 100.00 |
| Wall Stiffness (EI) | .136E+08 |

## STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 3.00 | .1410E+07 |
| 2 | 14.00 | .2090E+07 |
| 3 | 25.00 | .2090E+07 |

## MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 9.83 |
| Nondimensional System Stiffness = | 23.31 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 3.000 |
| Factor of safety against basal heave is | 8.1988 |
| Minimum factor of safety between stages is | 8.1988 |

| | |
|---|---|
| Average Strut Stiffness = | 1410000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .012 |
| Cantilever Movement at this Stage is | .308 |
| Total Wall Movement at this Stage is | .320 |
| Overall Maximum Lateral Wall Movement is | .320 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3200 | .1152 |
| 1.50 | .3200 | .2304 |
| 3.00 | .3040 | .2944 |
| 4.50 | .2400 | .3136 |
| 6.00 | .1920 | .3008 |
| 7.50 | .1440 | .2624 |
| 9.00 | .0960 | .2080 |
| 10.50 | .0800 | .1600 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 14.000 |
| Factor of safety against basal heave is | 2.7058 |
| Minimum factor of safety between stages is | 2.7058 |

| | |
|---|---|
| Average Strut Stiffness = | 1750000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .073 |
| Cantilever Movement at this Stage is | .227 |
| Total Wall Movement at this Stage is | .300 |
| Overall Maximum Lateral Wall Movement is | .320 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3200 | .1152 |
| 7.00 | .3200 | .2304 |
| 14.00 | .3040 | .2944 |
| 21.00 | .2400 | .3136 |
| 28.00 | .1920 | .3008 |
| 35.00 | .1440 | .2624 |
| 42.00 | .0960 | .2080 |
| 49.00 | .0800 | .1600 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 25.000 |
| Factor of safety against basal heave is | 1.8272 |
| Minimum factor of safety between stages is | 1.8272 |

| | |
|---|---|
| Average Strut Stiffness = | 1863333.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .74 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .252 |
| Cantilever Movement at this Stage is | .147 |
| Total Wall Movement at this Stage is | .398 |
| Overall Maximum Lateral Wall Movement is | .398 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3983 | .0648 |
| 12.50 | .3983 | .1466 |
| 25.00 | .3784 | .2204 |
| 37.50 | .2987 | .2067 |
| 50.00 | .2390 | .1558 |
| 62.50 | .1792 | .1099 |
| 75.00 | .1195 | .0770 |
| 87.50 | .0996 | .0501 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 32.500 |
| Factor of safety against basal heave is | 1.6819 |
| Minimum factor of safety between stages is | 1.6796 |

| | |
|---|---|
| Average Strut Stiffness = | 1863333.00 |
| Alpha D = | .91 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .353 |
| Cantilever Movement at this Stage is | .092 |
| Total Wall Movement at this Stage is | .445 |
| Overall Maximum Lateral Wall Movement is | .445 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .4447 | .1047 |
| 16.25 | .4447 | .2187 |
| 32.50 | .4225 | .2646 |
| 48.75 | .3335 | .2123 |
| 65.00 | .2668 | .1676 |
| 81.25 | .2001 | .1189 |
| 97.50 | .1334 | .0791 |
| 113.75 | .1112 | .0440 |

Table C.4

MOVEX Output for Case 2, Low Strength

PROGRAM MOVEX

QUAKER TOWER PROJECT, CHICAGO ILLINOIS, CLARK STREET, WEST WALL

The system of units used is English
The units of length are - Feet
The units of stress are - PSF

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .330 |
| Anticipated Hinge Depth = | 45.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 10.00 | Cohesion | .00 |
| Unit Weight | 120.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 38.50 | Cohesion | 600.00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 32.50 | Cohesion | 1500.00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 48.500

WATER TABLE DATA

Unit weight of water 62.40

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 120.00 |
| Total length of excavation | 210.00 |
| Final depth of excavation | 32.50 |
| Surcharge next to excavation | 100.00 |
| Wall Stiffness (EI) | .136E+08 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 3.00 | .1410E+07 |
| 2 | 14.00 | .2090E+07 |
| 3 | 25.00 | .2090E+07 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 9.83 |
| Nondimensional System Stiffness = | 23.31 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 3.000 |
| Factor of safety against basal heave is | 6.1491 |
| Minimum factor of safety between stages is | 6.1491 |

| | |
|---|---|
| Average Strut Stiffness = | 1410000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .012 |
| Cantilever Movement at this Stage is | .308 |
| Total Wall Movement at this Stage is | .320 |
| Overall Maximum Lateral Wall Movement is | .320 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3200 | .1152 |
| 1.50 | .3200 | .2304 |
| 3.00 | .3040 | .2944 |
| 4.50 | .2400 | .3136 |
| 6.00 | .1920 | .3008 |
| 7.50 | .1440 | .2624 |
| 9.00 | .0960 | .2080 |
| 10.50 | .0800 | .1600 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 14.000 |
| Factor of safety against basal heave is | 2.0012 |
| Minimum factor of safety between stages is | 2.0012 |

| | |
|---|---|
| Average Strut Stiffness = | 1750000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .112 |
| Cantilever Movement at this Stage is | .227 |
| Total Wall Movement at this Stage is | .340 |
| Overall Maximum Lateral Wall Movement is | .340 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3398 | .0612 |
| 7.00 | .3398 | .1380 |
| 14.00 | .3228 | .2129 |
| 21.00 | .2549 | .2178 |
| 28.00 | .2039 | .1660 |
| 35.00 | .1529 | .1198 |
| 42.00 | .1019 | .0906 |
| 49.00 | .0850 | .0640 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 25.000 |
| Factor of safety against basal heave is | 1.3022 |
| Minimum factor of safety between stages is | 1.3022 |

| | |
|---|---|
| Average Strut Stiffness = | 1863333.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .74 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .523 |
| Cantilever Movement at this Stage is | .147 |
| Total Wall Movement at this Stage is | .670 |
| Overall Maximum Lateral Wall Movement is | .670 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .6698 | .1008 |
| 12.50 | .6698 | .2283 |
| 25.00 | .6495 | .3353 |
| 37.50 | .4560 | .2882 |
| 50.00 | .3091 | .2145 |
| 62.50 | .2153 | .1475 |
| 75.00 | .1479 | .0939 |
| 87.50 | .1251 | .0537 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 32.500 |
| Factor of safety against basal heave is | 1.1404 |
| Minimum factor of safety between stages is | 1.1404 |

| | |
|---|---|
| Average Strut Stiffness = | 1863333.00 |
| Alpha D = | .91 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .900 |
| Cantilever Movement at this Stage is | .092 |
| Total Wall Movement at this Stage is | .992 |
| Overall Maximum Lateral Wall Movement is | .992 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .9919 | .0532 |
| 16.25 | .9919 | .1532 |
| 32.50 | .9780 | .3651 |
| 48.75 | .6191 | .3009 |
| 65.00 | .3455 | .2009 |
| 81.25 | .2145 | .1243 |
| 97.50 | .1549 | .0739 |
| 113.75 | .1338 | .0342 |

## Table C.5

## MOVEX Output for Case 3, High Strength

### PROGRAM MOVEX

900 NORTH MICHIGAN AVE, CHICAGO, "GENERIC" SOIL CONDITIONS

| | |
|---|---|
| The system of units used is | English |
| The units of length are - | Feet |
| The units of stress are - | PSF |

### CONTROL DATA

| | |
|---|---|
| Number of soil layers | 4 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

### CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .083 |
| Anticipated Hinge Depth = | 30.00 |

### SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | .00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 800.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 1000.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 2000.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 60.000

WATER TABLE DATA

| | |
|---|---|
| Unit weight of water | 62.40 |

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 230.00 |
| Total length of excavation | 440.00 |
| Final depth of excavation | 29.00 |
| Surcharge next to excavation | 650.00 |
| Wall Stiffness (EI) | .380E+08 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 4.00 | .5080E+03 |
| 2 | 12.00 | .1110E+07 |
| 3 | 24.00 | .1590E+07 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 8.33 |
| Nondimensional System Stiffness = | 126.28 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 4.000 |
| Factor of safety against basal heave is | 3.2572 |
| Minimum factor of safety between stages is | 3.2572 |
| Average Strut Stiffness = | 508.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | 1.73 |
| Lateral Wall Movement at this Stage is | .026 |
| Cantilever Movement at this Stage is | .072 |
| Total Wall Movement at this Stage is | .098 |
| Overall Maximum Lateral Wall Movement is | .098 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0981 | .0353 |
| 2.00 | .0981 | .0707 |
| 4.00 | .0932 | .0903 |
| 6.00 | .0736 | .0962 |
| 8.00 | .0589 | .0923 |
| 10.00 | .0442 | .0805 |
| 12.00 | .0294 | .0638 |
| 14.00 | .0245 | .0491 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 12.000 |
| Factor of safety against basal heave is | 2.1026 |
| Minimum factor of safety between stages is | 2.1026 |

| | |
|---|---|
| Average Strut Stiffness = | 555254.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .76 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .056 |
| Cantilever Movement at this Stage is | .050 |
| Total Wall Movement at this Stage is | .106 |
| Overall Maximum Lateral Wall Movement is | .106 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1063 | .0202 |
| 6.00 | .1063 | .0455 |
| 12.00 | .1010 | .0711 |
| 18.00 | .0797 | .0756 |
| 24.00 | .0638 | .0580 |
| 30.00 | .0478 | .0422 |
| 36.00 | .0319 | .0328 |
| 42.00 | .0266 | .0239 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 24.000 |
| Factor of safety against basal heave is | 1.5430 |
| Minimum factor of safety between stages is | 1.5430 |
| Average Strut Stiffness = | 900169.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .77 |
| Lateral Wall Movement at this Stage is | .187 |
| Cantilever Movement at this Stage is | .017 |
| Total Wall Movement at this Stage is | .204 |
| Overall Maximum Lateral Wall Movement is | .204 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2040 | .0417 |
| 12.00 | .2040 | .0892 |
| 24.00 | .1938 | .1144 |
| 36.00 | .1530 | .0939 |
| 48.00 | .1224 | .0727 |
| 60.00 | .0918 | .0511 |
| 72.00 | .0612 | .0335 |
| 84.00 | .0510 | .0188 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 29.000 |
| Factor of safety against basal heave is | 1.3709 |
| Minimum factor of safety between stages is | 1.3709 |
| Average Strut Stiffness = | 900169.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .79 |
| Lateral Wall Movement at this Stage is | .272 |
| Cantilever Movement at this Stage is | .003 |
| Total Wall Movement at this Stage is | .275 |
| Overall Maximum Lateral Wall Movement is | .275 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2750 | .0456 |
| 14.50 | .2750 | .1013 |
| 29.00 | .2648 | .1424 |
| 43.50 | .1938 | .1207 |
| 58.00 | .1401 | .0909 |
| 72.50 | .1007 | .0629 |
| 87.00 | .0683 | .0405 |
| 101.50 | .0574 | .0230 |

## Table C.6

## MOVEX Output for Case 3, Low Strength

PROGRAM MOVEX

900 NORTH MICHIGAN AVE, CHICAGO, "GENERIC" SOIL CONDITIONS

| | |
|---|---|
| The system of units used is | English |
| The units of length are - | Feet |
| The units of stress are - | PSF |

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 4 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .083 |
| Anticipated Hinge Depth = | 30.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | .00 |
| Unit Weight | 110.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 600.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 700.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 1500.00 |
| Unit Weight | 125.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 60.000

WATER TABLE DATA

| | |
|---|---|
| Unit weight of water | 62.40 |

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 230.00 |
| Total length of excavation | 440.00 |
| Final depth of excavation | 29.00 |
| Surcharge next to excavation | 650.00 |
| Wall Stiffness (EI) | .380E+08 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 4.00 | .5080E+03 |
| 2 | 12.00 | .1110E+07 |
| 3 | 24.00 | .1590E+07 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 8.33 |
| Nondimensional System Stiffness = | 126.28 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 4.000 |
| Factor of safety against basal heave is | 2.3524 |
| Minimum factor of safety between stages is | 2.3524 |

| | |
|---|---|
| Average Strut Stiffness = | 508.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | 1.73 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .038 |
| Cantilever Movement at this Stage is | .072 |
| Total Wall Movement at this Stage is | .110 |
| Overall Maximum Lateral Wall Movement is | .110 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1101 | .0355 |
| 2.00 | .1101 | .0722 |
| 4.00 | .1046 | .0958 |
| 6.00 | .0826 | .1027 |
| 8.00 | .0661 | .0946 |
| 10.00 | .0496 | .0804 |
| 12.00 | .0330 | .0637 |

| | | |
|---|---|---|
| 14.00 | .0275 | .0488 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 12.000 |
| Factor of safety against basal heave is | 1.5185 |
| Minimum factor of safety between stages is | 1.5185 |

| | |
|---|---|
| Average Strut Stiffness = | 555254.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .76 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .094 |
| Cantilever Movement at this Stage is | .050 |
| Total Wall Movement at this Stage is | .143 |
| Overall Maximum Lateral Wall Movement is | .143 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1434 | .0286 |
| 6.00 | .1434 | .0613 |
| 12.00 | .1362 | .0795 |
| 18.00 | .1075 | .0656 |
| 24.00 | .0860 | .0506 |
| 30.00 | .0645 | .0355 |
| 36.00 | .0430 | .0232 |
| 42.00 | .0358 | .0130 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 24.000 |
| Factor of safety against basal heave is | 1.1027 |
| Minimum factor of safety between stages is | 1.1027 |

| | |
|---|---|
| Average Strut Stiffness = | 900169.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .77 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .329 |
| Cantilever Movement at this Stage is | .017 |
| Total Wall Movement at this Stage is | .346 |
| Overall Maximum Lateral Wall Movement is | .346 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3459 | .0180 |
| 12.00 | .3459 | .0513 |
| 24.00 | .3423 | .1247 |
| 36.00 | .2113 | .0987 |
| 48.00 | .1113 | .0654 |
| 60.00 | .0663 | .0397 |
| 72.00 | .0488 | .0237 |
| 84.00 | .0425 | .0098 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 29.000 |
| Factor of safety against basal heave is | .9656 |
| Minimum factor of safety between stages is | .9656 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 900169.30 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .79 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .589 |
| Cantilever Movement at this Stage is | .003 |
| Total Wall Movement at this Stage is | .592 |
| Overall Maximum Lateral Wall Movement is | .592 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .5919 | .0296 |
| 14.50 | .5919 | .0829 |
| 29.00 | .5919 | .2072 |
| 43.50 | .3404 | .1539 |
| 58.00 | .1480 | .1006 |
| 72.50 | .0740 | .0592 |
| 87.00 | .0592 | .0355 |
| 101.50 | .0533 | .0118 |

Table C.7

MOVEX Output for Case A, High Strength

PROGRAM MOVEX

Telecom Building, Isotropic, Cantilever, Project A
High Strengths

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 5 |
| Number of struts | 6 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .010 |
| Anticipated Hinge Depth = | 20.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 1.00 | Cohesion | 10.00 |
| Unit Weight | 18.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 23.00 | Cohesion | 20.00 |
| Unit Weight | 16.00 | Coh. Increase | .80 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 2.00 | Cohesion | 10.00 |
| Unit Weight | 18.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 7.00 | Cohesion | 40.00 |
| Unit Weight | 18.00 | Coh. Increase | 5.70 |

Layer number 5

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 70.00 |

Unit Weight 18.50 Coh. Increase .00

Depth to firm layer from ground surface 35.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 27.00 |
| Total length of excavation | 42.60 |
| Final depth of excavation | 11.10 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .140E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 1.00 | .1290E+06 |
| 2 | 3.50 | .1290E+06 |
| 3 | 5.25 | .1590E+06 |
| 4 | 6.90 | .1590E+06 |
| 5 | 8.25 | .1590E+06 |
| 6 | 9.75 | .1590E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 1.68 |
| Nondimensional System Stiffness = | 177.10 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 1.000 |
| Factor of safety against basal heave is | 8.8872 |
| Minimum factor of safety between stages is | 8.8872 |

| | |
|---|---|
| Average Strut Stiffness = | 129000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .003 |
| Cantilever Movement at this Stage is | .009 |
| Total Wall Movement at this Stage is | .012 |
| Overall Maximum Lateral Wall Movement is | .012 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0124 | .0045 |
| .50 | .0124 | .0089 |
| 1.00 | .0118 | .0114 |
| 1.50 | .0093 | .0121 |
| 2.00 | .0074 | .0116 |
| 2.50 | .0056 | .0102 |
| 3.00 | .0037 | .0080 |
| 3.50 | .0031 | .0062 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 3.500 |
| Factor of safety against basal heave is | 3.0449 |
| Minimum factor of safety between stages is | 3.0449 |

| | |
|---|---|
| Average Strut Stiffness = | 129000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .010 |
| Cantilever Movement at this Stage is | .008 |
| Total Wall Movement at this Stage is | .018 |
| Overall Maximum Lateral Wall Movement is | .018 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0183 | .0066 |
| 1.75 | .0183 | .0132 |
| 3.50 | .0174 | .0169 |
| 5.25 | .0137 | .0180 |
| 7.00 | .0110 | .0172 |
| 8.75 | .0082 | .0150 |
| 10.50 | .0055 | .0119 |
| 12.25 | .0046 | .0092 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 5.250 |
| Factor of safety against basal heave is | 2.1485 |
| Minimum factor of safety between stages is | 2.1485 |

| | |
|---|---|
| Average Strut Stiffness = | 139000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .023 |
| Cantilever Movement at this Stage is | .007 |
| Total Wall Movement at this Stage is | .030 |
| Overall Maximum Lateral Wall Movement is | .030 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0301 | .0059 |
| 2.63 | .0301 | .0132 |
| 5.25 | .0286 | .0207 |
| 7.88 | .0226 | .0224 |
| 10.50 | .0181 | .0172 |
| 13.13 | .0135 | .0126 |
| 15.75 | .0090 | .0099 |
| 18.38 | .0075 | .0073 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 6.900 |
| Factor of safety against basal heave is | 1.5848 |
| Minimum factor of safety between stages is | 1.5848 |

| | |
|---|---|
| Average Strut Stiffness = | 144000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .047 |
| Cantilever Movement at this Stage is | .007 |
| Total Wall Movement at this Stage is | .054 |
| Overall Maximum Lateral Wall Movement is | .054 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0538 | .0115 |
| 3.45 | .0538 | .0244 |
| 6.90 | .0511 | .0307 |
| 10.35 | .0403 | .0250 |
| 13.80 | .0323 | .0195 |
| 17.25 | .0242 | .0137 |
| 20.70 | .0161 | .0091 |

| | | |
|---|---|---|
| 24.15 | .0134 | .0051 |

Excavation stage 5

| | |
|---|---|
| Height of excavation is | 8.250 |
| Factor of safety against basal heave is | 1.3755 |
| Minimum factor of safety between stages is | 1.3755 |

| | |
|---|---|
| Average Strut Stiffness = | 147000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.62 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .064 |
| Cantilever Movement at this Stage is | .006 |
| Total Wall Movement at this Stage is | .070 |
| Overall Maximum Lateral Wall Movement is | .070 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0702 | .0117 |
| 4.13 | .0702 | .0260 |
| 8.25 | .0676 | .0364 |
| 12.38 | .0496 | .0309 |
| 16.50 | .0360 | .0233 |
| 20.63 | .0259 | .0161 |
| 24.75 | .0176 | .0104 |
| 28.88 | .0148 | .0059 |

Excavation stage 6

| | |
|---|---|
| Height of excavation is | 9.750 |
| Factor of safety against basal heave is | 1.2444 |
| Minimum factor of safety between stages is | 1.2444 |

| | |
|---|---|
| Average Strut Stiffness = | 149000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.49 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .085 |
| Cantilever Movement at this Stage is | .005 |
| Total Wall Movement at this Stage is | .090 |
| Overall Maximum Lateral Wall Movement is | .090 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0901 | .0052 |
| 4.87 | .0901 | .0154 |
| 9.75 | .0879 | .0350 |
| 14.62 | .0595 | .0318 |
| 19.50 | .0379 | .0216 |
| 24.37 | .0256 | .0139 |
| 29.25 | .0178 | .0082 |
| 34.12 | .0152 | .0046 |

Excavation stage 7

| | |
|---|---|
| Height of excavation is | 11.100 |
| Factor of safety against basal heave is | 1.1735 |
| Minimum factor of safety between stages is | 1.1735 |

| | |
|---|---|
| Average Strut Stiffness = | 149000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.40 |
| Alpha S = | .74 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .099 |
| Cantilever Movement at this Stage is | .004 |
| Total Wall Movement at this Stage is | .104 |
| Overall Maximum Lateral Wall Movement is | .104 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1038 | .0057 |
| 5.55 | .1038 | .0166 |
| 11.10 | .1020 | .0389 |
| 16.65 | .0660 | .0332 |
| 22.20 | .0386 | .0223 |
| 27.75 | .0247 | .0140 |
| 33.30 | .0176 | .0083 |
| 38.85 | .0151 | .0041 |

Table C.8

MOVEX Output for Case A, Low Strength

PROGRAM MOVEX

Telecom Building, Isotropic, Cantilever, Project A
Low Strengths

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 5 |
| Number of struts | 6 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .010 |
| Anticipated Hinge Depth = | 20.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 1.00 | Cohesion | .00 |
| Unit Weight | 18.00 | Coh. Increase | 4.00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 23.00 | Cohesion | 4.00 |
| Unit Weight | 16.00 | Coh. Increase | 1.40 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 2.00 | Cohesion | 10.00 |
| Unit Weight | 18.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 7.00 | Cohesion | 40.00 |
| Unit Weight | 18.00 | Coh. Increase | 1.90 |

Layer number 5

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 70.00 |

| | | | |
|---|---|---|---|
| Unit Weight | 18.50 | Coh. Increase | .00 |

Depth to firm layer from ground surface 35.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 27.00 |
| Total length of excavation | 42.60 |
| Final depth of excavation | 11.10 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .140E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 1.00 | .1290E+06 |
| 2 | 3.50 | .1290E+06 |
| 3 | 5.25 | .1590E+06 |
| 4 | 6.90 | .1590E+06 |
| 5 | 8.25 | .1590E+06 |
| 6 | 9.75 | .1590E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 1.68 |
| Nondimensional System Stiffness = | 177.10 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 1.000 |
| Factor of safety against basal heave is | 5.4247 |
| Minimum factor of safety between stages is | 5.4247 |

| | |
|---|---|
| Average Strut Stiffness = | 129000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .003 |
| Cantilever Movement at this Stage is | .009 |
| Total Wall Movement at this Stage is | .012 |
| Overall Maximum Lateral Wall Movement is | .012 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0124 | .0045 |
| .50 | .0124 | .0089 |
| 1.00 | .0118 | .0114 |
| 1.50 | .0093 | .0121 |
| 2.00 | .0074 | .0116 |
| 2.50 | .0056 | .0102 |
| 3.00 | .0037 | .0080 |
| 3.50 | .0031 | .0062 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 3.500 |
| Factor of safety against basal heave is | 2.0441 |
| Minimum factor of safety between stages is | 2.0441 |

| | |
|---|---|
| Average Strut Stiffness = | 129000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .016 |
| Cantilever Movement at this Stage is | .008 |
| Total Wall Movement at this Stage is | .024 |
| Overall Maximum Lateral Wall Movement is | .024 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0240 | .0044 |
| 1.75 | .0240 | .0100 |
| 3.50 | .0228 | .0155 |
| 5.25 | .0180 | .0161 |
| 7.00 | .0144 | .0123 |
| 8.75 | .0108 | .0089 |
| 10.50 | .0072 | .0068 |
| 12.25 | .0060 | .0049 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 5.250 |
| Factor of safety against basal heave is | 1.5347 |
| Minimum factor of safety between stages is | 1.5347 |

| | |
|---|---|
| Average Strut Stiffness = | 139000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .037 |
| Cantilever Movement at this Stage is | .007 |
| Total Wall Movement at this Stage is | .045 |
| Overall Maximum Lateral Wall Movement is | .045 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0447 | .0091 |
| 2.63 | .0447 | .0194 |
| 5.25 | .0425 | .0250 |
| 7.88 | .0336 | .0206 |
| 10.50 | .0268 | .0159 |
| 13.13 | .0201 | .0112 |
| 15.75 | .0134 | .0073 |
| 18.38 | .0112 | .0041 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 6.900 |
| Factor of safety against basal heave is | 1.1742 |
| Minimum factor of safety between stages is | 1.1742 |

| | |
|---|---|
| Average Strut Stiffness = | 144000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .076 |
| Cantilever Movement at this Stage is | .007 |
| Total Wall Movement at this Stage is | .082 |
| Overall Maximum Lateral Wall Movement is | .082 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0823 | .0045 |
| 3.45 | .0823 | .0132 |
| 6.90 | .0809 | .0308 |
| 10.35 | .0523 | .0263 |
| 13.80 | .0306 | .0177 |
| 17.25 | .0196 | .0111 |
| 20.70 | .0140 | .0066 |

| | | |
|---|---|---|
| 24.15 | .0120 | .0033 |

Excavation stage 5

Height of excavation is 8.250
Factor of safety against basal heave is 1.0600
Minimum factor of safety between stages is 1.0600

Average Strut Stiffness = 147000.00
Alpha D = 1.00
Alpha B = 1.62
Alpha S = .75

Lateral Wall Movement at this Stage is .106
Cantilever Movement at this Stage is .006
Total Wall Movement at this Stage is .112
Overall Maximum Lateral Wall Movement is .112

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1120 | .0056 |
| 4.13 | .1120 | .0159 |
| 8.25 | .1113 | .0394 |
| 12.38 | .0668 | .0297 |
| 16.50 | .0327 | .0194 |
| 20.63 | .0184 | .0115 |
| 24.75 | .0139 | .0069 |
| 28.88 | .0122 | .0024 |

Excavation stage 6

Height of excavation is 9.750
Factor of safety against basal heave is .9852
Minimum factor of safety between stages is .9852

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

Average Strut Stiffness = 149000.00
Alpha D = 1.00
Alpha B = 1.49
Alpha S = .75

Lateral Wall Movement at this Stage is .138
Cantilever Movement at this Stage is .005
Total Wall Movement at this Stage is .143
Overall Maximum Lateral Wall Movement is .143

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1432 | .0072 |
| 4.87 | .1432 | .0200 |
| 9.75 | .1432 | .0501 |
| 14.62 | .0823 | .0372 |
| 19.50 | .0358 | .0243 |
| 24.37 | .0179 | .0143 |
| 29.25 | .0143 | .0086 |
| 34.12 | .0129 | .0029 |

Excavation stage 7

Height of excavation is 11.100
Factor of safety against basal heave is .9371
Minimum factor of safety between stages is .9371

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

Average Strut Stiffness = 149000.00
Alpha D = 1.00
Alpha B = 1.40
Alpha S = .74

Lateral Wall Movement at this Stage is .161
Cantilever Movement at this Stage is .004
Total Wall Movement at this Stage is .166
Overall Maximum Lateral Wall Movement is .166

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1658 | .0083 |
| 5.55 | .1658 | .0232 |
| 11.10 | .1658 | .0580 |
| 16.65 | .0953 | .0431 |
| 22.20 | .0415 | .0282 |
| 27.75 | .0207 | .0166 |
| 33.30 | .0166 | .0099 |
| 38.85 | .0149 | .0033 |

Table C.9

MOVEX Output for Case B, High Strength

PROGRAM MOVEX

Novena Station, Isotropic, Cantilever, Project B, High Strengths

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 5 |
| Number of struts | 6 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .100 |
| Anticipated Hinge Depth = | 30.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 2.00 | Cohesion | 10.00 |
| Unit Weight | 15.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 3.00 | Cohesion | 10.00 |
| Unit Weight | 14.00 | Coh. Increase | .00 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 1.50 | Cohesion | 10.00 |
| Unit Weight | 17.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 7.50 | Cohesion | 10.00 |
| Unit Weight | 15.00 | Coh. Increase | 1.10 |

Layer number 5

| | | | |
|---|---|---|---|
| Thickness | 20.00 | Cohesion | 70.00 |

Unit Weight 18.50 Coh. Increase .00

Depth to firm layer from ground surface 14.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 35.00 |
| Total length of excavation | 200.00 |
| Final depth of excavation | 14.70 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .234E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 1.00 | .9971E+05 |
| 2 | 3.00 | .9971E+05 |
| 3 | 5.50 | .1223E+06 |
| 4 | 7.50 | .1223E+06 |
| 5 | 9.50 | .1223E+06 |
| 6 | 11.80 | .1223E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 2.28 |
| Nondimensional System Stiffness = | 87.57 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 1.000 |
| Factor of safety against basal heave is | 4.5019 |
| Minimum factor of safety between stages is | 4.5019 |
| Average Strut Stiffness = | 99714.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .003 |
| Cantilever Movement at this Stage is | .097 |
| Total Wall Movement at this Stage is | .100 |
| Overall Maximum Lateral Wall Movement is | .100 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0997 | .0359 |
| .50 | .0997 | .0718 |
| 1.00 | .0947 | .0917 |
| 1.50 | .0748 | .0977 |
| 2.00 | .0598 | .0937 |
| 2.50 | .0449 | .0817 |
| 3.00 | .0299 | .0648 |
| 3.50 | .0249 | .0498 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 3.000 |
| Factor of safety against basal heave is | 1.6065 |
| Minimum factor of safety between stages is | 1.6065 |

| | |
|---|---|
| Average Strut Stiffness = | 99714.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .024 |
| Cantilever Movement at this Stage is | .090 |
| Total Wall Movement at this Stage is | .114 |
| Overall Maximum Lateral Wall Movement is | .114 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1139 | .0249 |
| 1.50 | .1139 | .0527 |
| 3.00 | .1082 | .0657 |
| 4.50 | .0855 | .0534 |
| 6.00 | .0684 | .0417 |
| 7.50 | .0513 | .0294 |
| 9.00 | .0342 | .0194 |
| 10.50 | .0285 | .0109 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 5.500 |
| Factor of safety against basal heave is | 0.9535 |
| Minimum factor of safety between stages is | 0.9535 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 107238.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .136 |
| Cantilever Movement at this Stage is | .082 |
| Total Wall Movement at this Stage is | .218 |
| Overall Maximum Lateral Wall Movement is | .218 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2179 | .0109 |
| 2.75 | .2179 | .0305 |
| 5.50 | .2179 | .0763 |
| 8.25 | .1253 | .0567 |
| 11.00 | .0545 | .0370 |
| 13.75 | .0272 | .0218 |
| 16.50 | .0218 | .0131 |
| 19.25 | .0196 | .0044 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 7.500 |
| Factor of safety against basal heave is | 0.7528 |
| Minimum factor of safety between stages is | 0.7528 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 111000.00 |
| Alpha D = | .99 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .213 |
| Cantilever Movement at this Stage is | .075 |
| Total Wall Movement at this Stage is | .288 |
| Overall Maximum Lateral Wall Movement is | .288 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2883 | .0144 |
| 3.75 | .2883 | .0404 |
| 7.50 | .2883 | .1009 |
| 11.25 | .1658 | .0749 |
| 15.00 | .0721 | .0490 |
| 18.75 | .0360 | .0288 |
| 22.50 | .0288 | .0173 |
| 26.25 | .0259 | .0058 |

Excavation stage 5

| | |
|---|---|
| Height of excavation is | 9.500 |
| Factor of safety against basal heave is | 0.6787 |
| Minimum factor of safety between stages is | 0.6787 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 113257.20 |
| Alpha D = | .90 |
| Alpha B = | 1.70 |
| Alpha S = | .74 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .244 |
| Cantilever Movement at this Stage is | .068 |
| Total Wall Movement at this Stage is | .312 |
| Overall Maximum Lateral Wall Movement is | .312 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3121 | .0156 |
| 4.75 | .3121 | .0437 |
| 9.50 | .3121 | .1092 |
| 14.25 | .1794 | .0811 |
| 19.00 | .0780 | .0531 |
| 23.75 | .0390 | .0312 |
| 28.50 | .0312 | .0187 |
| 33.25 | .0281 | .0062 |

Excavation stage 6

| | |
|---|---|
| Height of excavation is | 11.800 |
| Factor of safety against basal heave is | 0.7580 |
| Minimum factor of safety between stages is | 0.6734 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 114762.00 |
| Alpha D = | .75 |
| Alpha B = | 1.54 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .230 |
| Cantilever Movement at this Stage is | .061 |
| Total Wall Movement at this Stage is | .291 |
| Overall Maximum Lateral Wall Movement is | .312 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3121 | .0156 |
| 5.90 | .3121 | .0437 |
| 11.80 | .3121 | .1092 |
| 17.70 | .1794 | .0811 |
| 23.60 | .0780 | .0531 |
| 29.50 | .0390 | .0312 |
| 35.40 | .0312 | .0187 |
| 41.30 | .0281 | .0062 |

Excavation stage 7

| | |
|---|---|
| Height of excavation is | 14.700 |
| Factor of safety against basal heave is | 100.0000 |
| Minimum factor of safety between stages is | 0.6734 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 114762.00 |
| Alpha D = | .62 |
| Alpha B = | 1.38 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .214 |
| Cantilever Movement at this Stage is | .051 |
| Total Wall Movement at this Stage is | .265 |
| Overall Maximum Lateral Wall Movement is | .312 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3121 | .0156 |
| 7.35 | .3121 | .0437 |
| 14.70 | .3121 | .1092 |
| 22.05 | .1794 | .0811 |
| 29.40 | .0780 | .0531 |
| 36.75 | .0390 | .0312 |
| 44.10 | .0312 | .0187 |
| 51.45 | .0281 | .0062 |

Table C.10

MOVEX Output for Case B, Low Strength

PROGRAM MOVEX

Novena Station, Isotropic, Cantilever, Project B,
Low Strengths

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 5 |
| Number of struts | 6 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .100 |
| Anticipated Hinge Depth = | 30.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 2.00 | Cohesion | .00 |
| Unit Weight | 15.00 | Coh. Increase | 2.20 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 3.00 | Cohesion | 4.40 |
| Unit Weight | 14.00 | Coh. Increase | .90 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 1.50 | Cohesion | 10.00 |
| Unit Weight | 17.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 7.50 | Cohesion | 10.00 |
| Unit Weight | 15.00 | Coh. Increase | 1.10 |

Layer number 5

| | | | |
|---|---|---|---|
| Thickness | 40.00 | Cohesion | 70.00 |

Unit Weight 18.50 Coh. Increase .00

Depth to firm layer from ground surface 14.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 35.00 |
| Total length of excavation | 200.00 |
| Final depth of excavation | 14.70 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .234E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 1.00 | .9971E+05 |
| 2 | 3.00 | .9971E+05 |
| 3 | 5.50 | .1223E+06 |
| 4 | 7.50 | .1223E+06 |
| 5 | 9.50 | .1223E+06 |
| 6 | 11.80 | .1223E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 2.28 |
| Nondimensional System Stiffness = | 87.57 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 1.000 |
| Factor of safety against basal heave is | 3.7762 |
| Minimum factor of safety between stages is | 3.7762 |

| | |
|---|---|
| Average Strut Stiffness = | 99714.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .003 |
| Cantilever Movement at this Stage is | .097 |
| Total Wall Movement at this Stage is | .100 |
| Overall Maximum Lateral Wall Movement is | .100 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0997 | .0359 |
| .50 | .0997 | .0718 |
| 1.00 | .0947 | .0917 |
| 1.50 | .0748 | .0977 |
| 2.00 | .0598 | .0937 |
| 2.50 | .0449 | .0817 |
| 3.00 | .0299 | .0648 |
| 3.50 | .0249 | .0498 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 3.000 |
| Factor of safety against basal heave is | 1.4534 |
| Minimum factor of safety between stages is | 1.4534 |

| | |
|---|---|
| Average Strut Stiffness = | 99714.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .027 |
| Cantilever Movement at this Stage is | .090 |
| Total Wall Movement at this Stage is | .117 |
| Overall Maximum Lateral Wall Movement is | .117 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1170 | .0216 |
| 1.50 | .1170 | .0470 |
| 3.00 | .1117 | .0630 |
| 4.50 | .0859 | .0526 |
| 6.00 | .0664 | .0401 |
| 7.50 | .0491 | .0280 |
| 9.00 | .0329 | .0182 |
| 10.50 | .0275 | .0103 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 5.500 |
| Factor of safety against basal heave is | 0.9124 |
| Minimum factor of safety between stages is | 0.9124 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 107238.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .153 |
| Cantilever Movement at this Stage is | .082 |
| Total Wall Movement at this Stage is | .235 |
| Overall Maximum Lateral Wall Movement is | .235 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2347 | .0117 |
| 2.75 | .2347 | .0329 |
| 5.50 | .2347 | .0821 |
| 8.25 | .1350 | .0610 |
| 11.00 | .0587 | .0399 |
| 13.75 | .0293 | .0235 |
| 16.50 | .0235 | .0141 |
| 19.25 | .0211 | .0047 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 7.500 |
| Factor of safety against basal heave is | 0.7216 |
| Minimum factor of safety between stages is | 0.7216 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 111000.00 |
| Alpha D = | .99 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

Lateral Wall Movement at this Stage is .213
Cantilever Movement at this Stage is .075
Total Wall Movement at this Stage is .288
Overall Maximum Lateral Wall Movement is .288

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2883 | .0144 |
| 3.75 | .2883 | .0404 |
| 7.50 | .2883 | .1009 |
| 11.25 | .1658 | .0749 |
| 15.00 | .0721 | .0490 |
| 18.75 | .0360 | .0288 |
| 22.50 | .0288 | .0173 |
| 26.25 | .0259 | .0058 |

Excavation stage 5

Height of excavation is 9.500
Factor of safety against basal heave is 0.6449
Minimum factor of safety between stages is 0.6449

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

Average Strut Stiffness = 113257.20
Alpha D = .90
Alpha B = 1.70
Alpha S = .74

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

Lateral Wall Movement at this Stage is .244
Cantilever Movement at this Stage is .068
Total Wall Movement at this Stage is .312
Overall Maximum Lateral Wall Movement is .312

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3121 | .0156 |
| 4.75 | .3121 | .0437 |
| 9.50 | .3121 | .1092 |
| 14.25 | .1794 | .0811 |
| 19.00 | .0780 | .0531 |
| 23.75 | .0390 | .0312 |
| 28.50 | .0312 | .0187 |
| 33.25 | .0281 | .0062 |

Excavation stage 6

| | |
|---|---|
| Height of excavation is | 11.800 |
| Factor of safety against basal heave is | 0.6824 |
| Minimum factor of safety between stages is | 0.6347 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 114762.00 |
| Alpha D = | .75 |
| Alpha B = | 1.54 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .230 |
| Cantilever Movement at this Stage is | .061 |
| Total Wall Movement at this Stage is | .291 |
| Overall Maximum Lateral Wall Movement is | .312 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3121 | .0156 |
| 5.90 | .3121 | .0437 |
| 11.80 | .3121 | .1092 |
| 17.70 | .1794 | .0811 |
| 23.60 | .0780 | .0531 |
| 29.50 | .0390 | .0312 |
| 35.40 | .0312 | .0187 |
| 41.30 | .0281 | .0062 |

Excavation stage 7

| | |
|---|---|
| Height of excavation is | 14.700 |
| Factor of safety against basal heave is | 100.0000 |
| Minimum factor of safety between stages is | 0.6347 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 114762.00 |
| Alpha D = | .62 |
| Alpha B = | 1.38 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .214 |
| Cantilever Movement at this Stage is | .051 |
| Total Wall Movement at this Stage is | .265 |
| Overall Maximum Lateral Wall Movement is | .312 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .3121 | .0156 |
| 7.35 | .3121 | .0437 |
| 14.70 | .3121 | .1092 |
| 22.05 | .1794 | .0811 |
| 29.40 | .0780 | .0531 |
| 36.75 | .0390 | .0312 |
| 44.10 | .0312 | .0187 |
| 51.45 | .0281 | .0062 |

Table C.11

MOVEX Output for Case C, High Strength

PROGRAM MOVEX

Newton Cross-Over, No Cantilever, Project C, High Strengths

The system of units used is SI
The units of length are - Meters
The units of stress are - kPa

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 5 |
| Number of struts | 5 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .068 |
| Anticipated Hinge Depth = | 5.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 1.40 | Cohesion | 30.00 |
| Unit Weight | 17.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 8.60 | Cohesion | 10.00 |
| Unit Weight | 15.00 | Coh. Increase | .50 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 3.00 | Cohesion | 10.00 |
| Unit Weight | 17.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 7.00 | Cohesion | 19.00 |
| Unit Weight | 15.00 | Coh. Increase | 1.10 |

Layer number 5

| | | | |
|---|---|---|---|
| Thickness | 35.00 | Cohesion | 70.00 |
| Unit Weight | 18.50 | Coh. Increase | .00 |

| | |
|---|---|
| Depth to firm layer from ground surface | 55.000 |

WATER TABLE DATA

| | |
|---|---|
| Unit weight of water | 9.81 |

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 9.00 |
| Total length of excavation | 26.00 |
| Final depth of excavation | 15.00 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .456E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 1.50 | .1820E+06 |
| 2 | 5.00 | .2400E+06 |
| 3 | 7.50 | .3880E+06 |
| 4 | 10.50 | .3880E+06 |
| 5 | 13.00 | .3880E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 2.70 |
| Nondimensional System Stiffness = | 87.47 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 1.500 |
| Factor of safety against basal heave is | 3.3641 |
| Minimum factor of safety between stages is | 3.3641 |

| | |
|---|---|
| Average Strut Stiffness = | 182000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .005 |
| Cantilever Movement at this Stage is | .048 |
| Total Wall Movement at this Stage is | .052 |
| Overall Maximum Lateral Wall Movement is | .052 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0521 | .0188 |
| .75 | .0521 | .0375 |
| 1.50 | .0495 | .0479 |
| 2.25 | .0391 | .0511 |
| 3.00 | .0313 | .0490 |
| 3.75 | .0234 | .0427 |
| 4.50 | .0156 | .0339 |
| 5.25 | .0130 | .0261 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 5.000 |
| Factor of safety against basal heave is | 1.0231 |
| Minimum factor of safety between stages is | 1.0231 |

| | |
|---|---|
| Average Strut Stiffness = | 211000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.23 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .072 |
| Cantilever Movement at this Stage is | .000 |
| Total Wall Movement at this Stage is | .072 |
| Overall Maximum Lateral Wall Movement is | .072 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0723 | .0036 |
| 2.50 | .0723 | .0101 |
| 5.00 | .0722 | .0253 |
| 7.50 | .0422 | .0188 |
| 10.00 | .0193 | .0123 |
| 12.50 | .0101 | .0072 |
| 15.00 | .0079 | .0043 |
| 17.50 | .0070 | .0014 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 7.500 |
| Factor of safety against basal heave is | .6942 |
| Minimum factor of safety between stages is | .6942 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 270000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.09 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .138 |
| Overall Maximum Lateral Wall Movement is | .138 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1381 | .0069 |
| 3.75 | .1381 | .0193 |
| 7.50 | .1381 | .0483 |
| 11.25 | .0794 | .0359 |
| 15.00 | .0345 | .0235 |
| 18.75 | .0173 | .0138 |
| 22.50 | .0138 | .0083 |
| 26.25 | .0124 | .0028 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 10.500 |
| Factor of safety against basal heave is | .6501 |
| Minimum factor of safety between stages is | .6474 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 299500.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.01 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .180 |
| Overall Maximum Lateral Wall Movement is | .180 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1799 | .0090 |
| 5.25 | .1799 | .0252 |
| 10.50 | .1799 | .0630 |
| 15.75 | .1034 | .0468 |
| 21.00 | .0450 | .0306 |
| 26.25 | .0225 | .0180 |
| 31.50 | .0180 | .0108 |
| 36.75 | .0162 | .0036 |

Excavation stage 5

| | |
|---|---|
| Height of excavation is | 13.000 |
| Factor of safety against basal heave is | .6832 |
| Minimum factor of safety between stages is | .6474 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 317200.00 |
| Alpha D = | 1.00 |
| Alpha B = | .98 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .215 |
| Overall Maximum Lateral Wall Movement is | .215 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2153 | .0108 |
| 6.50 | .2153 | .0301 |
| 13.00 | .2153 | .0753 |
| 19.50 | .1238 | .0560 |
| 26.00 | .0538 | .0366 |
| 32.50 | .0269 | .0215 |
| 39.00 | .0215 | .0129 |
| 45.50 | .0194 | .0043 |

Excavation stage 6

| | |
|---|---|
| Height of excavation is | 15.000 |
| Factor of safety against basal heave is | .8969 |
| Minimum factor of safety between stages is | .6474 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 341657.20 |
| Alpha D = | 1.00 |
| Alpha B = | .96 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .244 |
| Overall Maximum Lateral Wall Movement is | .244 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2438 | .0122 |
| 7.50 | .2438 | .0341 |
| 15.00 | .2438 | .0853 |
| 22.50 | .1402 | .0634 |
| 30.00 | .0609 | .0414 |
| 37.50 | .0305 | .0244 |
| 45.00 | .0244 | .0146 |
| 52.50 | .0219 | .0049 |

Table C.12

MOVEX Output for Case C, Low Strength

PROGRAM MOVEX

Newton Cross-Over, No Cantilever, Project C, Low Strengths

| | |
|---|---|
| The system of units used is | SI |
| The units of length are - | Meters |
| The units of stress are - | kPa |

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 5 |
| Number of struts | 5 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

No Cantilever Movements are Anticipated

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 1.40 | Cohesion | .00 |
| Unit Weight | 17.00 | Coh. Increase | 3.10 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 8.60 | Cohesion | 4.40 |
| Unit Weight | 15.00 | Coh. Increase | 1.10 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 3.00 | Cohesion | 10.00 |
| Unit Weight | 17.00 | Coh. Increase | .00 |

Layer number 4

| | | | |
|---|---|---|---|
| Thickness | 7.00 | Cohesion | 19.00 |
| Unit Weight | 15.00 | Coh. Increase | 1.10 |

Layer number 5

| | | | |
|---|---|---|---|
| Thickness | 35.00 | Cohesion | 70.00 |
| Unit Weight | 18.50 | Coh. Increase | .00 |

| | |
|---|---|
| Depth to firm layer from ground surface | 55.000 |

WATER TABLE DATA

| | |
|---|---|
| Unit weight of water | 9.81 |

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 9.00 |
| Total length of excavation | 26.00 |
| Final depth of excavation | 15.00 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .456E+05 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | 1.50 | .1820E+06 |
| 2 | 5.00 | .2400E+06 |
| 3 | 7.50 | .3880E+06 |
| 4 | 10.50 | .3880E+06 |
| 5 | 13.00 | .3880E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 2.70 |
| Nondimensional System Stiffness = | 87.47 |

Excavation stage 1

| | |
|---|---|
| Height of excavation is | 1.500 |
| Factor of safety against basal heave is | 1.7229 |
| Minimum factor of safety between stages is | 1.7229 |
| Average Strut Stiffness = | 182000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .011 |
| Overall Maximum Lateral Wall Movement is | .011 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0108 | .0016 |
| .75 | .0108 | .0037 |
| 1.50 | .0103 | .0055 |
| 2.25 | .0081 | .0048 |
| 3.00 | .0065 | .0036 |
| 3.75 | .0049 | .0025 |
| 4.50 | .0032 | .0016 |
| 5.25 | .0027 | .0010 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 5.000 |
| Factor of safety against basal heave is | .7896 |
| Minimum factor of safety between stages is | .7896 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 211000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.23 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .104 |
| Overall Maximum Lateral Wall Movement is | .104 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1043 | .0052 |
| 2.50 | .1043 | .0146 |
| 5.00 | .1043 | .0365 |
| 7.50 | .0600 | .0271 |
| 10.00 | .0261 | .0177 |
| 12.50 | .0130 | .0104 |
| 15.00 | .0104 | .0063 |
| 17.50 | .0094 | .0021 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 7.500 |
| Factor of safety against basal heave is | .6071 |
| Minimum factor of safety between stages is | .6071 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 270000.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.09 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .138 |
| Overall Maximum Lateral Wall Movement is | .138 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1381 | .0069 |
| 3.75 | .1381 | .0193 |
| 7.50 | .1381 | .0483 |
| 11.25 | .0794 | .0359 |
| 15.00 | .0345 | .0235 |
| 18.75 | .0173 | .0138 |
| 22.50 | .0138 | .0083 |
| 26.25 | .0124 | .0028 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 10.500 |
| Factor of safety against basal heave is | .6047 |
| Minimum factor of safety between stages is | .5990 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 299500.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.01 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

Lateral Wall Movement at this Stage is .180
Overall Maximum Lateral Wall Movement is .180

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1799 | .0090 |
| 5.25 | .1799 | .0252 |
| 10.50 | .1799 | .0630 |
| 15.75 | .1034 | .0468 |
| 21.00 | .0450 | .0306 |
| 26.25 | .0225 | .0180 |
| 31.50 | .0180 | .0108 |
| 36.75 | .0162 | .0036 |

Excavation stage 5

Height of excavation is 13.000
Factor of safety against basal heave is .6454
Minimum factor of safety between stages is .5990

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

Average Strut Stiffness = 317200.00
Alpha D = 1.00
Alpha B = .98
Alpha S = .75

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

Lateral Wall Movement at this Stage is .215
Overall Maximum Lateral Wall Movement is .215

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2153 | .0108 |
| 6.50 | .2153 | .0301 |
| 13.00 | .2153 | .0753 |
| 19.50 | .1238 | .0560 |
| 26.00 | .0538 | .0366 |
| 32.50 | .0269 | .0215 |
| 39.00 | .0215 | .0129 |
| 45.50 | .0194 | .0043 |

Excavation stage 6

| | |
|---|---|
| Height of excavation is | 15.000 |
| Factor of safety against basal heave is | .8528 |
| Minimum factor of safety between stages is | .5990 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 317200.00 |
| Alpha D = | 1.00 |
| Alpha B = | .96 |
| Alpha S = | .75 |

THE GIVEN WALL SYSTEM MAY HAVE EXCESSIVE MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF SAFETY. PLEASE CHECK INPUT VALUES OF STRUT SPACING & STIFFNESS AND WALL STIFFNESS FOR ACCURACY.

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .244 |
| Overall Maximum Lateral Wall Movement is | .244 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .2438 | .0122 |
| 7.50 | .2438 | .0341 |
| 15.00 | .2438 | .0853 |
| 22.50 | .1402 | .0634 |
| 30.00 | .0609 | .0414 |
| 37.50 | .0305 | .0244 |
| 45.00 | .0244 | .0146 |
| 52.50 | .0219 | .0049 |

## Table C.13

## MOVEX Output for Case D, High Strength

### PROGRAM MOVEX

Newton Station, Singapore, Diaphragm Wall, Project D, High Su

| | |
|---|---|
| The system of units used is | SI |
| The units of length are - | Meters |
| The units of stress are - | kPa |

### CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

### CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .060 |
| Anticipated Hinge Depth = | 16.00 |

### SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 3.00 | Cohesion | 30.00 |
| Unit Weight | 17.00 | Coh. Increase | .00 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 10.00 | Cohesion | 15.00 |
| Unit Weight | 16.00 | Coh. Increase | .60 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 1.00 | Cohesion | 30.00 |
| Unit Weight | 19.00 | Coh. Increase | .00 |

Depth to firm layer from ground surface 14.000

### WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 21.20 |
| Total length of excavation | 100.00 |
| Final depth of excavation | 13.30 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .120E+07 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | .00 | .1189E+07 |
| 2 | 2.00 | .1189E+07 |
| 3 | 7.00 | .4623E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 4.43 |
| Nondimensional System Stiffness = | 315.50 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 2.000 |
| Factor of safety against basal heave is | 3.5945 |
| Minimum factor of safety between stages is | 3.5945 |
| Average Strut Stiffness = | 1188679.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .005 |
| Cantilever Movement at this Stage is | .052 |
| Total Wall Movement at this Stage is | .058 |
| Overall Maximum Lateral Wall Movement is | .100 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0997 | .0359 |
| 1.00 | .0997 | .0718 |
| 2.00 | .0947 | .0917 |
| 3.00 | .0748 | .0977 |
| 4.00 | .0598 | .0937 |
| 5.00 | .0449 | .0817 |
| 6.00 | .0299 | .0648 |
| 7.00 | .0249 | .0498 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 7.000 |
| Factor of safety against basal heave is | 1.1639 |
| Minimum factor of safety between stages is | 1.1639 |
| Average Strut Stiffness = | 946540.70 |
| Alpha D = | 1.00 |
| Alpha B = | 1.56 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .060 |
| Cantilever Movement at this Stage is | .034 |
| Total Wall Movement at this Stage is | .093 |
| Overall Maximum Lateral Wall Movement is | .100 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0997 | .0054 |
| 3.50 | .0997 | .0158 |
| 7.00 | .0980 | .0372 |
| 10.50 | .0630 | .0314 |
| 14.00 | .0364 | .0210 |
| 17.50 | .0231 | .0131 |
| 21.00 | .0165 | .0078 |
| 24.50 | .0142 | .0038 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 13.300 |
| Factor of safety against basal heave is | 100.0000 |
| Minimum factor of safety between stages is | 1.0465 |
| Average Strut Stiffness = | 987302.70 |
| Alpha D = | .66 |
| Alpha B = | 1.18 |
| Alpha S = | .75 |
| Lateral Wall Movement at this Stage is | .074 |
| Cantilever Movement at this Stage is | .010 |
| Total Wall Movement at this Stage is | .084 |
| Overall Maximum Lateral Wall Movement is | .100 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0997 | .0050 |
| 6.65 | .0997 | .0140 |
| 13.30 | .0992 | .0349 |
| 19.95 | .0589 | .0259 |
| 26.60 | .0282 | .0169 |
| 33.25 | .0155 | .0100 |
| 39.90 | .0118 | .0060 |
| 46.55 | .0105 | .0020 |

Table C.14

MOVEX Output for Case D, Low Strength

PROGRAM MOVEX

Newton Station, Singapore, Diaphragm Wall, Project D,
Low Su

| | |
|---|---|
| The system of units used is | SI |
| The units of length are - | Meters |
| The units of stress are - | kPa |

CONTROL DATA

| | |
|---|---|
| Number of soil layers | 3 |
| Number of struts | 3 |
| Design Option | 0 |
| Anisotropic Strength Ratio | 1.000 |

CANTILEVER EFFECT

| | |
|---|---|
| Expected Cantilever Movement at Top = | .060 |
| Anticipated Hinge Depth = | 16.00 |

SOIL LAYER DATA

Layer number 1

| | | | |
|---|---|---|---|
| Thickness | 3.00 | Cohesion | .00 |
| Unit Weight | 17.00 | Coh. Increase | 2.30 |

Layer number 2

| | | | |
|---|---|---|---|
| Thickness | 10.00 | Cohesion | 6.90 |
| Unit Weight | 16.00 | Coh. Increase | 1.40 |

Layer number 3

| | | | |
|---|---|---|---|
| Thickness | 1.00 | Cohesion | 20.50 |
| Unit Weight | 19.00 | Coh. Increase | 2.00 |

Depth to firm layer from ground surface 14.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

| | |
|---|---|
| Total width of excavation | 21.20 |
| Total length of excavation | 100.00 |
| Final depth of excavation | 13.30 |
| Surcharge next to excavation | .00 |
| Wall Stiffness (EI) | .120E+07 |

STRUT DATA

| Strut | Depth | Stiffness |
|---|---|---|
| 1 | .00 | .1189E+07 |
| 2 | 2.00 | .1189E+07 |
| 3 | 7.00 | .4623E+06 |

MOVEMENT CALCULATIONS

| | |
|---|---|
| Average Strut Spacing = | 4.43 |
| Nondimensional System Stiffness = | 315.50 |

Excavation stage 2

| | |
|---|---|
| Height of excavation is | 2.000 |
| Factor of safety against basal heave is | 2.1480 |
| Minimum factor of safety between stages is | 2.1480 |

| | |
|---|---|
| Average Strut Stiffness = | 1188679.00 |
| Alpha D = | 1.00 |
| Alpha B = | 1.70 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .007 |
| Cantilever Movement at this Stage is | .052 |
| Total Wall Movement at this Stage is | .060 |
| Overall Maximum Lateral Wall Movement is | .100 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .0997 | .0194 |
| 1.00 | .0997 | .0437 |
| 2.00 | .0947 | .0686 |
| 3.00 | .0748 | .0741 |
| 4.00 | .0598 | .0569 |
| 5.00 | .0449 | .0416 |
| 6.00 | .0299 | .0327 |
| 7.00 | .0249 | .0240 |

Excavation stage 3

| | |
|---|---|
| Height of excavation is | 7.000 |
| Factor of safety against basal heave is | .8392 |
| Minimum factor of safety between stages is | .8392 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 946540.70 |
| Alpha D = | 1.00 |
| Alpha B = | 1.56 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .105 |
| Cantilever Movement at this Stage is | .034 |
| Total Wall Movement at this Stage is | .139 |
| Overall Maximum Lateral Wall Movement is | .139 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1390 | .0070 |
| 3.50 | .1390 | .0195 |
| 7.00 | .1390 | .0487 |
| 10.50 | .0799 | .0361 |
| 14.00 | .0348 | .0236 |
| 17.50 | .0174 | .0139 |
| 21.00 | .0139 | .0083 |
| 24.50 | .0125 | .0028 |

Excavation stage 4

| | |
|---|---|
| Height of excavation is | 13.300 |
| Factor of safety against basal heave is | 100.0000 |
| Minimum factor of safety between stages is | .7258 |

**CAUTION: Factor of safety is less than 1.0**
Values obtained are for factor of safety = 0.9 case.

| | |
|---|---|
| Average Strut Stiffness = | 987302.70 |
| Alpha D = | .66 |
| Alpha B = | 1.18 |
| Alpha S = | .75 |

| | |
|---|---|
| Lateral Wall Movement at this Stage is | .100 |
| Cantilever Movement at this Stage is | .010 |
| Total Wall Movement at this Stage is | .111 |
| Overall Maximum Lateral Wall Movement is | .139 |

Est. Distribution of Ground Surface Movement

| Dist. fr. Wall | Vert. Disp. | Lat. Disp. |
|---|---|---|
| .00 | .1390 | .0070 |
| 6.65 | .1390 | .0195 |
| 13.30 | .1390 | .0487 |
| 19.95 | .0799 | .0361 |
| 26.60 | .0348 | .0236 |
| 33.25 | .0174 | .0139 |
| 39.90 | .0139 | .0083 |
| 46.55 | .0125 | .0028 |

Appendix D

MOVEX Program Listing

```
      PROGRAM MOVEX
c
c     PROGRAM MOVEX  -  1987
c
c  Program for design of excavation bracing to limit ground
c  movement.  Based on the design method by Mana and Clough
c  (1981), and Clough and Buchignani 1981).  First version
cof program written by Susumu Sunami (1981); second version
c  written by Sybil Goessling (1986); third version written
c  by Maureen Smith (1986); current version written by
c     Elizabeth M. Smith (1988).
c
   DIMENSION h(20),c0(20),dc(20),gt(20),l(20),j(20),hs(20),
     1         fs(20),disp(20),d(8,20),s(20),dv(8,20),
     2  dl(8,20),fsel(20),fsmd(20),fselmn(20),akx(6),aky(6)
  CHARACTER fin*14,fout*14,title*72,unit*11,leng*15,forc*15
      COMMON de,hw,b,q,io,eln,CE,CEM,CEH,xks
      DATA akx/0.0,0.25,0.50,0.75,1.00,1.25/,
     1     aky/0.615,0.68,0.77,0.875,1.00,1.125/
c.................TITLE PAGE..............................
c
 10   WRITE(*,20)
 20
FORMAT(//////////15X,'*************************************'/
     1         15X,' *                                   *'/
     2         15X,' *              MOVEX                *'/
     3         15X,' *                                   *'/
     4         15X,' *    A program for the design of    *'/
     5         15X,' *excavation bracing to limit lateral*'/
     6         15X,' *     ground movements in clays.    *'/
     7         15X,' *                                   *'/
     8         15X,'**************************************')
c
      WRITE(*,30)
 30   FORMAT(///20X,'NAME OF INPUT FILE:'/
     1         20X,' (e.g. b:xyz.dat) --> '\)
      READ(*,40) fin
 40   FORMAT(A14)
 160  WRITE(*,170)
 170  FORMAT(//20X,' OUTPUT DESTINATION: '//
     1         20X,'    0 = Screen '/
     2         20X,'    1 = Printer'/
     3         20X,'    2 = Disk '//
     4         20X,' PLEASE SPECIFY --> '\)
      READ(*,180) io
 180  FORMAT(I5)
      IF(io.LT.0.OR.io.GT.2) GO TO 160
      IF(io.LT.2) WRITE(*,190)
 190  FORMAT(//20X,' Press "RETURN" to continue. '//)
      IF(io.EQ.2) WRITE(*,200)
```

```
 200   FORMAT(//20X,' NAME OF OUTPUT FILE: '/
     1          20X,' (e.g. b:xyz.out) --> '\)
       READ(*,40) fout
c
       IF(io.EQ.1) OPEN(1,FILE='PRN')
       OPEN(5,FILE=fin,STATUS='OLD',ACCESS='SEQUENTIAL')
       IF(io.EQ.2)
OPEN(2,FILE=fout,STATUS='NEW',ACCESS='SEQUENTIAL')
       REWIND 5
       WRITE(io,210)
 210   FORMAT(1H1,T5,'PROGRAM MOVEX'/
     1        1H+,T5,'_____________')
c
c.....................READ AND WRITE THE INPUT DATA......
c
       READ(5,220) title
 220   FORMAT(A72)
       WRITE(io,230) title
 230   FORMAT(1H,'       ',A72)
 235   READ (5,*) unit,leng,forc
       WRITE(io,240) unit
 240   FORMAT(1H0,T5,'The system of units used is ',' ',A11)
       WRITE(io,250) leng,forc
 250   FORMAT(1H,T5,'The units of length are  -  ',' ',A15,/
     1        1H,T5,'The units of stress are  -  ','  ',A15)
       READ(5,*) mopt,nopt
       READ(5,*) nlay,nstrt,xks
       WRITE(io,260) nlay,nstrt,nopt,xks
 260   FORMAT(1H0,T5,'CONTROL DATA'/
     a        1H+,T5,'____________'//
     1        1H,T10,'Number of soil layers',T40,I5/
     2        1H,T10,'Number of struts',T40,I5/
     3        1H,T10,'Design Option',T43,I2/
     4        1H,T10,'Anisotropic Strength Ratio',T39,F6.3)
c
       READ(5,*) CE,CEM,CEH
       WRITE(io,263)
       IF (CE.EQ.0) WRITE (io,264)
       IF (CE.EQ.1) THEN
         WRITE (io,265) CEM,CEH
       ENDIF
 263   FORMAT(1H0,T5,'CANTILEVER EFFECT'/
     a        1H+,T5,'_________________')
 264   FORMAT(1H0,T10,'No Cantilever Movements are
Anticipated')
 265   FORMAT(1H0,T10,'Expected Cantilever Movement at Top
                      =',T51,F6.3/
     a        1H,T10,'Anticipated Hinge Depth =',T50,F6.2)
       WRITE(io,270)
 270   FORMAT(1H0,T5,'SOIL LAYER DATA'/
```

```
a       1H+,T5,'________________')
      READ(5,*)(j(i),h(i),gt(i),c0(i),dc(i),i=1,nlay)
      READ(5,*) df
      de=0
      DO 280 i=1,nlay
         WRITE(io,300) i
         WRITE(io,310) h(i),c0(i)
         WRITE (io,320) gt(i),dc(i)
         de=de+h(i)
 280  CONTINUE
      WRITE(io,290) df
 290  FORMAT(1H0,T10,'Depth to firm layer from ground
       surface',T50,F9.3)
 300  FORMAT(1H0,T10,'Layer number  ',I2,/)
 310  FORMAT(T15,'Thickness',T30,F6.2,T40,'Cohesion',
              T60,F8.2)
 320  FORMAT(T15,'Unit Weight',T30,F6.2,T40,'Coh.Increase',
              T60,F8.2)
c
      READ(5,*) gw
      WRITE(io,330) gw
 330  FORMAT(1H0,T5,'WATER TABLE DATA'/
     a        1H+,T5,'________________'//
     1       1H,T10,'Unit weight of water',T40,F7.2)
      IF(gw.EQ.0.) gw=1.0
c
      READ(5,*) b,eln,hw,q
      WRITE(io,340) b,eln,hw,q
 340  FORMAT(1H0,T5,'EXCAVATION GEOMETRY'/
     a        1H+,T5,'____________________',//
     1       1H,T10,'Total width of excavation',7X,F10.2,/
     2       1H,T10,'Total length of excavation',6X,F10.2/
     3       1H,T10,'Final depth of excavation ',6X,F10.2,/
     4       1H,T10,'Surcharge next to excavation',5X,F9.2,)
c
      hstrt=0.0
      shs=0.0
      havg=0.0
      savg=0.0
      sss=0.0
      ms=nstrt
c
      IF(nopt.EQ.0) GOTO 350
      IF(nopt.EQ.1) GOTO 450
      IF(nopt.EQ.2) GOTO 470
      IF(nopt.EQ.3) GOTO 510
c
c     ...........nopt=0 input...........
c
 350  READ(5,*) ei
```

```
       READ(5,*) (l(i),hs(i),s(i),i=1,nstrt)
       WRITE(io,360) ei
 360   FORMAT(T10,'Wall Stiffness (EI)',11X,E12.3)
 370   WRITE(io,380)
 380   FORMAT(1H0,T5,'STRUT DATA'/
      a        1H+,T5,'__________',/
      1        1H0,T10,'Strut     Depth      Stiffness',/)
      2        1H0)
       DO 390 i=1,nstrt
          hstrt=hstrt+hs(i)
          WRITE(io,410) l(i),hstrt,s(i)
 390    CONTINUE

       IF(hstrt.LT.hw) THEN
          ms=ms+1
          hs(ms)=hw-hstrt
       ENDIF
 410   FORMAT(T11,I2,T20,F5.2,1X,E13.4)
c
 420   WRITE(io,*)'       '
       IF(nopt.EQ.0) WRITE(io,430)
 430   FORMAT(1H1,'    MOVEMENT CALCULATIONS'/
      1        1H+,'    _____________________')
       IF(nopt.EQ.1) WRITE(io,440)
 440   FORMAT(1H1,'    WALL STIFFNESS CALCULATIONS'/
      1        1H+,'    ___________________________')
       GOTO 563
c
c      ...........nopt=1 input............
c
 450   READ(5,*) dlm
       WRITE(io,460) dlm
 460   FORMAT(T10,'Max. allowable vert. displacement',
                2X,F7.2)
       READ(5,*) (l(i),hs(i),s(i),i=1,nstrt)
       GOTO 370
c
c      ...........nopt=2 input..........
c
 470   READ(5,*) dlm
       WRITE(io,460) dlm
       READ(5,*) ei
       WRITE(io,360) ei
       READ(5,*) savg
       WRITE(io,480) savg
 480   FORMAT(T10,'Average strut stiffness',6X,E13.4)
       WRITE(io,490)
 490   FORMAT(1H0,T5,'STRUT SPACING CALCULATIONS'/
      1        1H+,T5,'__________________________')
       ms=5
```

```
      DO 500 i=1,5
         hs(i)=hw/5
 500  CONTINUE
      GOTO 563
c
c     ........nopt = 3 input..........
c
 510  READ(5,*) dlm
      WRITE(io,460) dlm
      READ(5,*) ei
      WRITE(io,360) ei
      READ(5,*) (l(i),hs(i),i=1,nstrt)
      WRITE(io,520)
 520  FORMAT(1H0,T5,'STRUT DATA'/
     a        1H+,T5,'__________'/
     1        1H0,T10,'Strut    Depth',/)
      DO 530 i=1,nstrt
         hstrt=hstrt+hs(i)
         WRITE(io,540) l(i),hstrt
 530  CONTINUE
 540  FORMAT(T11,I2,T19,F5.2)
      IF(hstrt.LT.hw) THEN
         ms=ms+1
         hs(ms)=hw-hstrt
      ENDIF
      WRITE(io,545)
 545  FORMAT(1H0,T5,'STRUT STIFFNESS CALCULATIONS'/
     1        1H+,T5,'____________________________')
      GOTO 563
c
c...............INTERACTIVE CHANGES IN THE
DESIGN...................
c
 550  WRITE(*,560)fin
 560  FORMAT(//20X,'NAME OF NEW FILE TO BE WRITTEN: '/
    1 20X,'Current file name is ',A14,' and all unchanged'/
    2 20x,'values will come from this file.Please specify'/
    3 20x,'new file name, or the current file if you wish'/
    4 20x,'for it to be changed.'/
    2 20X,'   (e.g. B:xyz.dat) --> '\)
      READ(*,40) fin
      OPEN(5,FILE=fin,STATUS='NEW',ACCESS='SEQUENTIAL')
      CALL CHNG(mopt,nopt,ei,nstrt,hs,s,title,nlay,df,gw,
     1          dc,gt,h,j,c0,l,dlm,savg,unit,leng,forc)
      GOTO 160
c
c..............ALPHA K (ANISOTROPIC STRENGTH CALCULATIONS)
c
 563  n=6
      IF (xks.LE.0.0) THEN
```

```
            ak = 0.615
            GOTO 565
        ENDIF
        IF (xks.GE.1.25) THEN
            ak = 1.125
            GOTO 565
        ENDIF
        IF (xks.EQ.1.0) THEN
            ak = 1.0
            GOTO 565
        ENDIF
        CALL COEFS (n,akx,aky,xks,ak)
 565    CONTINUE
*       WRITE (io,*) 'KS =',xks,'ALPHA K =',ak
c
c.....COMPUTE AVERAGE STRUT SPACING..........
c
        IF (nopt.EQ.2) GOTO 570
        DO 567 i=2,nstrt
        shs = shs + hs(i)
 567    CONTINUE
          IF (hstrt.LT.hw) THEN
             mstrt = nstrt
             shs = shs + (hw-hstrt)
          ELSE
             mstrt = nstrt - 1
          ENDIF
        havg = shs/mstrt
        WRITE(io,595) havg
 595    FORMAT(1H0,T15,'Average Strut Spacing =',T59,F7.2)
c
c.....compute system stiffness
c
        systf=ALOG10(ei/((havg**4.0)*gw))
c
        WRITE (io,55) 10**systf
 55     FORMAT(T15,'Nondimensional System Stiffness =
',T54,F12.2)
c
c.......................CONTROL CALCULATIONS...........
c
 570    DO 600 m=1,ms
           nx=m
           IF(hs(1).EQ.0.0) THEN
              IF(m.EQ.1) THEN
                 sss=sss + s(m)
                 GOTO 600
              ELSE
                 nx=m-1
              ENDIF
```

```
          ENDIF
          IF(nopt.EQ.2) GOTO 590
          WRITE(io,580) m
 580      FORMAT(1H0,T10,'Excavation stage ',I2/)
 590      k=m-1
          CALL FSHEAV(hs,m,k,gw,nlay,h,c0,dc,gt,fs,gm,he,
     1                 df,nopt,fselmn,ak)
c
          IF(nopt.GE.2) GOTO 600
c    compute average strut stiffness..........
            sss=sss+s(m)
             IF (m .GT. nstrt) THEN
                savg = sss/nstrt
             ELSE
                savg=sss/m
             ENDIF
      WRITE(io,596) savg
 596  FORMAT(1H0,T15,'Average Strut Stiffness =',T54,
F12.2)
          IF(nopt.EQ.1) GOTO 600
      CALL SDISP(fs,disp,dlm,gm,he,ei,havg,savg,df,m,nopt,
     1  gw,fselmn,CE,CEM,CEH,systf)
      IF(mopt.EQ.0) CALL DSTRB(m,fs,he,disp,d,dv,dl,fselmn)
 600  CONTINUE
c
      IF(nopt.EQ.0) GOTO 630
      IF(nopt.EQ.1) THEN
         CALL SDISP(fs,disp,dlm,gm,hw,ei,havg,savg,df,ms,
     1  nopt,gw,fselmn,CE,CEM,CEH,systf)
         IF(mopt.EQ.0) THEN
            disp(ms)=dlm
            CALL DSTRB(ms,fs,hw,disp,d,dv,dl,fselmn)
         ENDIF
         GOTO 630
      ENDIF
      IF(nopt.GE.2) THEN
         IF(nopt.EQ.2) THEN
           WRITE(io,610) fs(ms)
           IF(fs(ms).LT.1.0) WRITE(io,620)
         ENDIF
 610  FORMAT(1H0,T15,'Min. factor of safety for the excav.
         = ',F7.4)
 620  FORMAT(T15,'**CAUTION: Factor of safety is less than
          1.0**'/
     1  1H,T13,'Values obtained are for factor of safety =
          0.9 case.')
      CALL SDISP(fs,disp,dlm,gm,hw,ei,havg,savg,df,ms,nopt,
     1  gw,fselmn,CE,CEM,CEH,systf)
         IF(mopt.EQ.0) THEN
            disp(ms)=dlm
```

```
            CALL DSTRB(ms,fs,hw,disp,d,dv,dl,fselmn)
         ENDIF
      ENDIF
c
 630  CLOSE (5)
      IF(io.EQ.1) CLOSE (1)
      IF(io.EQ.2) CLOSE (2)
      WRITE(*,640)
 640  FORMAT(1H0,20X,'  ')
      WRITE(*,650)
 650  FORMAT(/////20X,' 1.  MAKE CHANGES TO THE DESIGN'//
     1            20X,' 2.  RUN A NEW PROBLEM'//
     2            20X,' 3.  EXIT TO DOS  '///
     3            20X,' Please Specify 1, 2, or 3 ---> '\)
      READ(*,180) iopt
      IF(iopt.EQ.1) GOTO 550
      IF(iopt.EQ.2) GOTO 10
c
 660  STOP
      END
```

```
c ........SUBROUTINE FSHEAV ........
c
   SUBROUTINE FSHEAV (hs,m,k,gw,nlay,h,c0,dc,gt,fs,gm,
  1                    he,df,nopt,fselmn,ak)
c
   DIMENSION hs(20), h(20), c0(20), dc(20), gt(20), fs(20),
     1          fsel(20), fsmd(20),fselmn(20),hsum(20),
     2          t(20),botlay(20),fsdf(20),dcrit(20)
      COMMON   de,hw,b,q,io,eln
c
      IF (m.EQ.1) hei=0.0
      IF (m.GT.1) THEN
        IF (hs(m-1).EQ.0.0) THEN
            hei=0.0
            fselmn(1)=100
        ENDIF
      ENDIF
      iend=0
      fselmn(m)=100
      fselmn(0)=100
      fs(0)=100
c
c ........Excavating between struts in 10 steps........
c
      DO 200 i=1,10
        hei=hei+(0.1* hs(m))
c
c......set initial values.......
        fsmd(i)=100.0
        hsum(0)=0
        t(0)=0
        pe=0
        rc=0
        hside=0
        htob=0
        Tfail=0
        HT=0
        tsum=0
        subt=0
        subb=0
        sub=0
        bresis=0
        fsel(i)=100.0
        gm=0
        dfirm=df
        botlay(0)=0
        ndf=0
        dcrit(i)=df

c
```

```
c..evaluates soil layers of influence on given excav. depth
c
          DO 100 j=1,nlay
c
c......add next soil layer........
c
            hsum(j)=hsum(j-1)+h(j)
c
c..compute effects of soil layer j if above excav. bottom
c
      IF (hsum(j).LE.hei)THEN
c
c..rc = resistance to sliding (from cohesion) on vertical
c......failure plane.....
c
          rc = rc+(c0(j)+dc(j)*h(j)/2)*h(j)
c
c..pe = total stress sum (bearing stress due to soil weight
c......of layers adjacent to excavation.
c
          pe = pe+gt(j)*h(j)

c
c......loops back if excav. bottom has not been reached
c
          IF (hsum(j).LT.hei) THEN
             t(j)=0
             GOTO 100
          ENDIF
      ENDIF
c
c..adds effects of portions of layers above excav. bottom
c......where hside = layer thickness above excav. bottom
c
      IF (hsum(j).GT.hei.AND.hsum(j-1).LE.hei) THEN
         hside = hei-hsum(j-1)
         rc = rc+(c0(j)+dc(j)*hside/2)*hside
         pe = pe+gt(j)*hside
      ENDIF
c
c
c..evaluate the bottom of all soil layers for critical
c.depth to failure surface (the failure surface which gives
c.the lowest factor of safety for that excavation depth)
c........botlay(n) = depth to bottom of soil layer n
c........ndf = number of soil layers below excav. bottom
c
      DO 40 n=1,nlay
         botlay(n) = botlay(n-1)+h(n)
        IF (botlay(n).LT.hei) THEN
```

```
                ndf=0
                GOTO 40
            ELSE
                ndf=ndf+1
                botlay(ndf)=botlay(n)
            ENDIF
 40     CONTINUE
        IF (ndf.EQ.0) WRITE(io,45)
 45     FORMAT(1H0,T15,'THE TOTAL DEPTH OF THE SOIL LAYERS'/
       1 1H,T15,'MUST BE DEEPER THAN THE EXCAVATION DEPTH')
c
c
c......compute depth to failure surface....
c...where htob is depth to failure surface from ground
c.surface, defined by H plus 0.7B, and depth to firm layer
c....is dfirm
c Tfail is the distance from excav. bottom to failure
c... surface
c.HT is the smaller of htob and dfirm, is the actual depth
c........to failure surface defined by H plus Tfail
c
      DO 80 n=1,ndf
c
      b7 = 0.7*b
      htob = hei + b7
c
      IF (botlay(n).LT.df) THEN
         dfirm = botlay(n)
      ELSE
         dfirm = df
      ENDIF
c
      IF (dfirm.LT.htob) THEN
            Tfail = dfirm-hei
      ELSE
            Tfail = htob - hei
      ENDIF
      HT = hei+Tfail
c
c....evaluate soil layers providing bearing resistance
c....tsum is the sum of layer thicknesses between excav.
c......bottom and failure surface
c....t(j) is the thickness of layer j, portion of layer
c......below excav. bottom only
c
      IF (hsum(j).LE.HT) THEN
        tsum = hsum(j)-hei
            IF (hsum(j-1).LE.hei) THEN
               t(j) = tsum
            ELSE
```

```
              t(j) = tsum - t(j-1)
           ENDIF
      ELSE
        tsum = Tfail
        t(j) = tsum - t(j-1)
      ENDIF
c
c.compute bearing resistance of layers below excav. bottom
c.subt = undrained shear strength of layer j at top oflayer
c.where "top" is defined as at or below excav. bottom
c.subb=undrained shear strength of layer j at bottomoflayer
c.where "bottom" is defined as at or above failure surface
c
      IF (hsum(j-1).LT.hei) THEN
            subt = c0(j) + dc(j)*(hei-hsum(j-1))
            subb = subt+dc(j)*t(j)
      ELSE
            subt = c0(j)
            subb = c0(j) + dc(j)*t(j)
      ENDIF
c
c.sub = average of subt and subb (used for layers
c.........increasing in shear strength with depth)
c.bresis = bearing resistance sum provided by soil layers
c.........below excav. bottom and above failure surface
c
      sub = (subt + subb)/2
      bresis = bresis + sub*t(j)
c
c.....loops back to consider all soil layers to failure
c......surface before calculating factor of safety
c
      t(j)=t(j)+t(j-1)
      IF (hsum(j).LT.HT) GOTO 100
c
c........Bearing capacity factor........
c
 50          bcf=5*(1.0+0.2*(b/eln))
c
c.........factor of safety..........
c
            IF (((pe+q)*Tfail).LE.rc) THEN
              IF (j.EQ.1) fsmd(j)=fs(m-1)
              IF (j.GT.1) fsmd(j)=fsmd(j-1)
              GOTO 100
            ENDIF
c
c
c.computes new factor of safety for each firm layer...
c...............(ak = anisotropic strength ratio)
```

```
c
          fsdf(n)=(bcf*bresis*ak)/((pe+q)*Tfail-rc)
c
c...........computes minimum factor of safety between the
c...........different firm layers
c
          IF (fsmd(j).GT.fsdf(n)) THEN
              fsmd(j)=fsdf(n)
              dcrit(j)=dfirm
          ENDIF
c
c
 80   CONTINUE
c
c............computes minimum factor of safety..........
             IF (fsel(i).GT.fsmd(j)) THEN
                 fsel(i)=fsmd(j)
                 dcrit(i)=dcrit(j)
             ENDIF
c
c.stops iterating if depth has reached failure surface or
c.............firm layer....
c
             IF (hsum(j).GE.HT) GOTO 101
c
 100       CONTINUE
c
 101      IF (fsel(i).LT.fselmn(m)) THEN
              fselmn(m)=fsel(i)
              dcrit(m)=dcrit(i)
          ENDIF
         IF (fselmn(m).GT.fselmn(m-1)) fselmn(m)=fselmn(m-1)
c
         fs(m)=fsel(10)
 200     CONTINUE
         he=hei
         IF (nopt.EQ.2) GOTO 615
c
 210     WRITE (io,211)hei
 211     FORMAT (T15,'Depth of excavation is  ',F10.3)
        WRITE (io,216) fs(m)
        WRITE (io,217) fselmn(m)
        WRITE (io,218) dcrit(m)
 216    FORMAT (T15,'Factor of safety against basal heave
          is',F8.4)
 217    FORMAT (T15,'Minimum factor of safety between stages
          is  ',F8.4)
 218    FORMAT (T15,'Bottom of failure surface at minimum FS
          is  ',F8.4)
c
```

```
      IF (fselmn(m).LT.1.0) WRITE (io,219)
 219  FORMAT (1H0,T15,'**CAUTION: Factor of safety is less
       than 1.0*'/
     1  1H,T13,'Values obtained are for factor of safety =
       0.9 case.')
c
 615  RETURN
      END
```

```
c.............SUBROUTINE SDISP - FINDS DISPLACEMENT
c
      SUBROUTINE SDISP(fs,disp,dlm,gm,he,ei,havg,savg,df,m,
     1                 nopt,gw,fselmn,CE,CEM,CEH,systf)
      DIMENSION fsx9(11),fsy9(11),fsx10(11),fsy10(11),
     1          fsx11(11),fsy11(11),fsx14(11),fsy14(11),
     2          fsx20(11),fsy20(11), fsx30(11),fsy30(11),
     3         fsx10a(11),fsy10a(11),fsx11a(11), fsy11a(11),
     a         fsx14a(11),fsy14a(11),fsx20a(11),fsy20a(11),
     4           fsx30a(11),fsy30a(11),adx(4),ady(4),abx(4),
     5          aby(4),asx(4),asy(4),asxa(4),asya(4),fs(20),
     6         s(20),disp(20),fsx(11),fsy(11),asxl(4),
     a          asyal(4),fselmn(20),fsxa(11),fsya(11),
     7           fsxb(11),fsyb(11),fsx9a(11),fsy9a(11)
      COMMON de,hw,b,q,io,eln
c
      DATA fsx9/70.0,80.0,100.0,150.0,175.0,200.0,300.0,
     1           500.0,700.0,1000.0,3000.0/,
     1 fsy9/3.0,2.50,2.0,1.625,1.50,1.45,1.30,1.22,
        1.15,1.10,1.0/,fsx10/50.0,58.0,70.0,82.0,100.0,15
     1  0.0,200.0,300.0,500.0,1000.0,3000.0/,fsy10/3.0,
     2  .5,2.0, 1.75,1.55,1.3,1.2,1.1,1.0,
     3  0.92,0.825/, fsx11/20.0,30.0,50.0,70.0,80.0,
     4  100.0,150.0,200.0,300.0,700.0,3000.0/,
     5  fsy11/2.85,2.2,1.6,1.3,1.25,1.125,1.0,0.9,
     6  0.8,0.67,0.55/,fsx14/10.0,20.0,30.0,50.0,70.0,
     7  100.0,200.0,300.0,500.0,1000.0,3000.0/,
     8  fsy14/2.1,1.3,1.1,0.9,0.8,0.7,0.6,0.525,0.45,
     9  0.375,0.3/,fsx20/10.0,20.0,30.0,50.0,70.0,100.0,
     1  200.0,300.0,500.0,1000.0,3000.0/,
     2  fsy20/0.83,0.65,0.6,0.5,0.45,0.4,0.35,0.3,0.275,
     3  0.25,0.2/,fsx30/10.0,20.0,30.0,50.0,70.0,100.0,
     4  200.0,300.0,500.0,1000.0,3000.0/,
     5  fsy30/0.43,0.325,0.3,0.25,0.25,0.225,0.225,0.2,
     6  0.2,0.175,0.15/
      DATA fsx9a/1.0,1.10,1.15,1.22,1.30,1.45,1.50,1.625,
     1  2.0,2.50,3.0/,fsy9a/3000.0,1000.0,700.0,500.0,
     2  300.0,200.0,175.0,150.0,100.0,80.0,70.0/,
     3  fsx10a/0.825,0.9,1.0,1.1,1.2,1.3,1.55,1.75,2.0,
     4  2.5,3.0/,fsy10a/3000.0,1000.0,500.0,300.0,200.0,
     5  150.0,100.0,82.0,70.0,58.0,50.0/,fsx11a/0.55,
     6  0.67,0.8,0.9,1.0,1.125,1.25,1.3,1.6,2.2,2.85/,
     2   fsy11a/3000.0,700.0,300.0,200.0,150.0,100.0,
     3   80.0, 70.0,50.0,30.0,20.0/,fsx14a/0.3,0.375,
     4  0.45,0.525,0.6,0.7,0.8,0.9,1.1,1.3,2.1/,
     5  fsy14a/3000.0,1000.0,500.0,300.0,200.0,100.0,
     6   70.0,50.0,30.0,20.0,10.0/,
     7   fsx20a/0.2,0.25,0.275,0.3,0.35,0.4,0.45,0.5,
     8   0.6,0.65,0.83/,fsy20a/3000.0,1000.0,500.0,
     9   300.0,200.0,100.0,70.0,50.0,30.0,20.0,10.0/,
```

```
     1     fsx30a/0.15,0.175,0.2,0.2,0.225,0.225,0.25,
     2     0.25,0.3,0.325,0.43/,
     3    fsy30a/3000.0,1000.0,500.0,300.0,200.0,
     4    100.0,70.0,50.0,30.0,20.0,10.0/
      DATA adx/1.0,1.4,1.66,2.0/,
     6     ady/0.62,0.87,0.96,1.0/,
     7     abx/0.8,1.67,3.2,4.0/,
     8     aby/1.0,1.2,1.6,1.8/,
     9     asx/60.0,133.3,533.3,1666.7/,
     1     asy/1.17,1.0,0.785,0.75/,
     2     asxa/1666.7,533.3,133.3,60.0/,
     3     asya/0.75,0.785,1.0,1.17/
c
c.....alfa d (depth to firm layer)........
c
      n=4
      ds=df/he
      IF(ds.LE.1.0) THEN
         ad=0.62
         GOTO 10
      ENDIF
      IF(ds.GE.2.0) THEN
         ad=1.0
         GOTO 10
      ENDIF
      CALL COEFS(n,adx,ady,ds,ad)
 10    CONTINUE
c
      WRITE(io,15) ad
 15   FORMAT(T15,'Alpha D = ',T59,F7.2)
c
c......alfa b (excavation width)..........
c
      n=4
      bs=b/he
      IF(bs.LE.0.5) THEN
         ab=0.9
         GOTO 20
      ENDIF
      IF(bs.GE.3.5) THEN
         ab=1.7
         GOTO 20
      ENDIF
      CALL COEFS(n,abx,aby,bs,ab)
 20    CONTINUE
c
      WRITE(io,25)ab
 25   FORMAT(T15,'Alpha B = ',T59,F7.2)
c
      IF(nopt.EQ.3) GOTO 50
```

```
c
c......alfa s (strut stiffness)...........
c
      n=4
      DO 30 i=1,n
         asxl(i)=ALOG10(asx(i))
 30   CONTINUE
      stf=ALOG10(savg/(gw*he))
      IF(stf.GE.3.22) THEN
         as=0.75
         GOTO 40
      ENDIF
      CALL COEFS(n,asxl,asy,stf,as)
c
 40   CONTINUE
c
      WRITE(io,45) as
 45   FORMAT(T15,'Alpha S = ',T52,F14.2)
c
      IF(nopt.EQ.0) GOTO 50
      IF(nopt.EQ.1) GOTO 140
      IF(nopt.EQ.2) GOTO 140
c
c..........NOPT = 0 (find maximum displacement).........
c
 50   n=11
c
C.WRITES WARNING MESSAGE IF STIFFNESS EXCEEDS DATA CURVES
C
      IF(systf.GE.3.5) THEN
        WRITE (io,310)
        systf = 3.5
      ENDIF
c
C.....WRITES WARNING MESSAGE IF STIFFNESS IS VERY LOW
C
          IF(systf.LT.1.0) THEN
            IF(fselmn(m).GE.1.4) THEN
               WRITE (io,320)
            ENDIF
          systf = 1.0
          ENDIF
      IF(fselmn(m).GE.3.0) THEN
            DO 60 i=1,11
               fsx(i)=fsx30(i)
               fsy(i)=fsy30(i)
 60         CONTINUE
            DO 65 i=1,11
               fsx(i)=ALOG10(fsx(i))
 65         CONTINUE
```

```
            CALL COEFS(n,fsx,fsy,systf,dh)
            GOTO 120
      ENDIF
C
C.CALCULATES LINEAR INTERPOLATION BETWEEN 3>FS>=2 CURVES
C
      IF(fselmn(m).GE.2.0.AND.fselmn(m).LT.3.0) THEN
            DO 70 i=1,11
               fsxa(i)=fsx20(i)
               fsya(i)=fsy20(i)
 70         CONTINUE
            DO 75 i=1,11
               fsxb(i)=fsx30(i)
               fsyb(i)=fsy30(i)
 75         CONTINUE
            FSA=2.0
            FSB=3.0
      ENDIF
C
C.CALCULATES LINEAR INTERPOLATION BETWEEN 2>FS>=1.4 CURVES
C
      IF(fselmn(m).GE.1.4.AND.fselmn(m).LT.2.0) THEN
            DO 80 i=1,11
               fsxa(i)=fsx14(i)
               fsya(i)=fsy14(i)
 80         CONTINUE
            DO 85 i=1,11
               fsxb(i)=fsx20(i)
               fsyb(i)=fsy20(i)
 85         CONTINUE
            FSA=1.4
            FSB=2.0
      ENDIF
C
CCALCULATES LINEAR INTERPOLATION BETWEEN 1.4>FS>=1.1 CURVES
C
      IF(fselmn(m).GE.1.1.AND.fselmn(m).LT.1.4) THEN
            IF(systf.LE.1.3) THEN
               WRITE (io,330)
            ENDIF
            DO 90 i=1,11
               fsxa(i)=fsx11(i)
               fsya(i)=fsy11(i)
 90         CONTINUE
            DO 95 i=1,11
               fsxb(i)=fsx14(i)
               fsyb(i)=fsy14(i)
 95         CONTINUE
            FSA=1.1
            FSB=1.4
```

```
      ENDIF
c
CALCULATES LINEAR INTERPOLATION BETWEEN 1.1>FS>=1.0 CURVES.
c
      IF(fselmn(m).GE.1.0.AND.fselmn(m).LT.1.1) THEN
         IF(systf.LE.1.7) THEN
            WRITE (io,330)
         ENDIF
         DO 100 i=1,11
            fsxa(i)=fsx10(i)
            fsya(i)=fsy10(i)
 100        CONTINUE
            DO 101 i=1,11
               fsxb(i)=fsx11(i)
               fsyb(i)=fsy11(i)
 101        CONTINUE
            FSA=1.0
            FSB=1.1
      ENDIF
CALCULATES LINEAR INTERPOLATION BETWEEN 1.0>FS>=0.9 CURVES.
c
      IF(fselmn(m).GE.0.9.AND.fselmn(m).LT.1.0) THEN
         IF(systf.LE.1.95) THEN
            WRITE (io,330)
         ENDIF
         DO 102 i=1,11
            fsxa(i)=fsx9(i)
            fsya(i)=fsy9(i)
 102        CONTINUE
            DO 103 i=1,11
               fsxb(i)=fsx10(i)
               fsyb(i)=fsy10(i)
 103        CONTINUE
            FSA=0.9
            FSB=1.0
      ENDIF
C
C.COMPUTES MOVEMENTS FOR FS<0.9 USING FS=0.9 CURVES
C
      IF(fselmn(m).LT.0.9) THEN
            IF(systf.LE.1.95) THEN
              WRITE(io,330)
            ENDIF
            DO 106 i=1,11
               fsx(i)=fsx9(i)
               fsy(i)=fsy9(i)
 106        CONTINUE
            DO 107 i=1,11
               fsx(i)=ALOG10(fsx(i))
 107        CONTINUE
```

```
            CALL COEFS(n,fsx,fsy,systf,dh)
            GOTO 120
      ENDIF
      DO 110 i=1,11
         fsxa(i)=ALOG10(fsxa(i))
         fsxb(i)=ALOG10(fsxb(i))
 110  CONTINUE
c
c............COMPUTE AVERAGE FROM GIVEN CURVES............
c
      CALL COEFS(n,fsxa,fsya,systf,dha)
      CALL COEFS(n,fsxb,fsyb,systf,dhb)
c
      dh=dhb-(((FSB-fselmn(m))/(FSB-FSA))*(dhb-dha))
c
c.....(to be used for debugging)
*     WRITE(io,*)'dh=',dh,' dha=',dha,' dhb=',dhb
c
 120  IF(nopt.EQ.3) GOTO 260
C
C.....COMPUTES MAX. LATERAL WALL MOVEMENTS.................
      disp(m)=dh*ad*ab*as*he*0.01
      WRITE(io,121) disp(m)
 121  FORMAT(1H0,T15,'Lateral Wall Movement at this Stage .
      is',F10.3)
c
c...............COMPUTES CANTILEVER EFFECT.................
c
 125  IF (CE.EQ.1.AND.he.LE.CEH) THEN
         ux=CEM*(CEH-he)/CEH
         disp(m)=disp(m)+ux
         WRITE(io,126) ux
 126 FORMAT(T15,'Cantilever Movement at this Stage is',
      F10.3)
         WRITE(io,127) disp(m)
 127 FORMAT(T15,'Total Wall Movement at this Stage is ',
       F10.3)
      ENDIF
c
c.....Sets Displacement Equal to MAXIMUM amount...........
c
      IF (disp(m).LT.disp(m-1)) disp(m)=disp(m-1)
c
      WRITE(io,130) disp(m)
 130 FORMAT(T15,'Overall Maximum Lateral Wall Movement is',
        F10.3)
      GOTO 300
c
c........nopt=1 and nopt=2 curves.......
c
```

```
 140   n=11
       dh=dlm/(ad*ab*as)
       IF(fselmn(m).GE.3.0) THEN
              IF(dh.GE.0.43) THEN
                 WRITE (io,340)
              ENDIF
              IF(dh.LE.0.15) THEN
                 WRITE (io,350)
              ENDIF
              DO 150 i=1,11
                 fsx(i)=fsx30a(i)
                 fsy(i)=fsy30a(i)
 150          CONTINUE
              DO 155 i=1,11
                 fsy(i)=ALOG10(fsy(i))
 155          CONTINUE
              CALL COEFS(n,fsx,fsy,dh,systf)
              GOTO 205
       ENDIF
C
C.COMPUTES LINEAR INTERPOLATION BETWEEN 3>FS>=2.0 CURVES
C
       IF(fselmn(m).GE.2.0.AND.fselmn(m).LT.3.0) THEN
              IF(dh.GE.0.83) THEN
                 WRITE (io,340)
              ENDIF
              IF(dh.LE.0.2) THEN
                 WRITE (io,350)
              ENDIF
              DO 160 i=1,11
                 fsxa(i)=fsx20a(i)
                 fsya(i)=fsy20a(i)
 160           CONTINUE
              DO 165 i=1,11
                 fsxb(i)=fsx30a(i)
                 fsyb(i)=fsy30a(i)
 165          CONTINUE
              FSA=2.0
              FSB=3.0
       ENDIF
C
C.COMPUTES LINEAR INTERPOLATION BETWEEN 2>FS>=1.4 CURVES
C
       IF(fselmn(m).GE.1.4.AND.fselmn(m).LT.2.0) THEN
              IF(dh.GE.2.1) THEN
                 WRITE (io,340)
              ENDIF
              IF(dh.LE.0.3) THEN
                 WRITE (io,350)
              ENDIF
```

```
              DO 170 i=1,11
                 fsxa(i)=fsx14a(i)
                 fsya(i)=fsy14a(i)
 170           CONTINUE
              DO 175 i=1,11
                 fsxb(i)=fsx20a(i)
                 fsyb(i)=fsy20a(i)
 175          CONTINUE
              FSA=1.4
              FSB=2.0
         ENDIF
C
C.COMPUTES LINEAR INTERPOLATION BETWEEN 1.4>FS>=1.1 CURVES
C
         IF(fselmn(m).GE.1.1.AND.fselmn(m).LT.1.4) THEN
              IF(dh.GE.2.85) THEN
                 WRITE (io,360)
              ENDIF
              IF(dh.LE.0.55) THEN
                 WRITE (io,350)
              ENDIF
              DO 180 i=1,11
                 fsxa(i)=fsx11a(i)
                 fsya(i)=fsy11a(i)
 180           CONTINUE
              DO 185 i=1,11
                 fsxb(i)=fsx14a(i)
                 fsyb(i)=fsy14a(i)
 185          CONTINUE
              FSA=1.1
              FSB=1.4
         ENDIF
C
C.COMPUTES LINEAR INTERPOLATION BETWEEN 1.1>FS>=1.0 CURVES
C
         IF(fselmn(m).GE.1.0.AND.fselmn(m).LT.1.1) THEN
            IF(dh.GE.3.0) THEN
                 WRITE (io,360)
            ENDIF
            IF(dh.LE.0.825) THEN
                 WRITE (io,350)
            ENDIF
            DO 190 i=1,11
               fsxa(i)=fsx10a(i)
               fsya(i)=fsy10a(i)
 190        CONTINUE
              DO 191 i=1,11
                 fsxb(i)=fsx11a(i)
                 fsyb(i)=fsy11a(i)
 191          CONTINUE
```

```
            FSA=1.0
            FSB=1.1
      ENDIF
C.COMPUTES LINEAR INTERPOLATION BETWEEN 1.0>FS>=0.9 CURVES
C
      IF(fselmn(m).GE.0.9.AND.fselmn(m).LT.1.0) THEN
         IF(dh.GE.3.0) THEN
               WRITE (io,360)
         ENDIF
         IF(dh.LE.1.085) THEN
               WRITE (io,350)
         ENDIF
         DO 193 i=1,11
            fsxa(i)=fsx9a(i)
            fsya(i)=fsy9a(i)
 193      CONTINUE
            DO 194 i=1,11
               fsxb(i)=fsx10a(i)
               fsyb(i)=fsy10a(i)
 194        CONTINUE
            FSA=0.9
            FSB=1.0
      ENDIF
C
C.COMPUTES MOVEMENTS FOR FS<0.9 USING FS=0.9 CURVES
C
      IF(fselmn(m).LT.0.9) THEN
            IF(dh.GE.3.0) THEN
               WRITE (io,360)
            ENDIF
            IF(dh.LE.1.085) THEN
               WRITE (io,350)
            ENDIF
            DO 197 i=1,11
               fsx(i)=fsx9a(i)
               fsy(i)=fsy9a(i)
 197        CONTINUE
            DO 198 i=1,11
               fsy(i)=ALOG10(fsy(i))
 198        CONTINUE
            CALL COEFS(n,fsx,fsy,dh,systf)
            GOTO 205
      ENDIF
      DO 200 i=1,11
         fsya(i)=ALOG10(fsya(i))
         fsyb(i)=ALOG10(fsyb(i))
 200  CONTINUE
      CALL COEFS(n,fsxa,fsya,dh,systfa)
      CALL COEFS(n,fsxb,fsyb,dh,systfb)
C
```

```
c......COMPUTES SYSTEM STIFFNESS REQUIRED
c
 systf=systfb-(((FSB-fselmn(m))/(FSB-FSA))*(systfb-systfa))
c
 205  CONTINUE
      IF(nopt.EQ.2) GOTO 230
c
c.........nopt=1 calculations (find wall stiffness).....
c
 210  ei=(10.0**systf)*gw*(havg**4.0)
      WRITE(io,220) ei
 220  FORMAT(1H0,T10,'  Required wall stiffness = ',E10.3)
      GOTO 300
c
c.........nopt=2 calculations (find strut spacing)........
c
 230  CONTINUE
 240  havg=(ei/((10.0**systf)*gw))**0.25
      WRITE(io,250) havg
 250  FORMAT(1H0,T10,'Required averagestrutspacing=',F10.3)
      GOTO 300
c
c.........nopt=3 calculations (find strut stiffness)......
c
 260  n=4
      DO 270 i=1,n
         asyal(i)=ALOG10(asya(i))
 270  CONTINUE
      as=dlm/((dh/100)*he*ad*ab)
      IF(as.LE.0.75) THEN
         sstf=1666.7
         savg=sstf*gw*he
         GOTO 285
      ENDIF
      IF(as.GE.1.3) THEN
         sstf=50
         savg=sstf*gw*he
         GOTO 285
      ENDIF
      CALL COEFS(n,asxa,asyal,as,sstf)
 280  savg=(10.0**sstf)*gw*he
 285  CONTINUE
      WRITE(io,290) savg
 290  FORMAT(1H0,T10,'Required average strut stiffness =',
       E13.4)
c
 300  CONTINUE
      RETURN
c
c.....disclaimer statements
```

```
C
 310  FORMAT(1H0,T20,'THE GIVEN SYSTEM IS VERY STIFF AND
EXCEEDS'/
  1 1H,T20,'THE AVAILABLE DATA CURVES. PLEASE VERIFYINPUT'/
  1 1H,T20,'VALUES OF STRUT STIFFNESS & SPACING AND WALL'/
  2 1H,T20,'STIFFNESS.')
 320  FORMAT(1H0,T20,'THE GIVEN SYSTEM IS EXTREMELY
FLEXIBLE AND WALL'/
  1 1H,T20,'MOVEMENTS MAY BE EXCESSIVE. PLEASEVERIFYINPUT'/
  2 1H,T20,'VALUES OF STRUT STIFFNESS & SPACING AND WALL'/
  3 1H,T20,'STIFFNESS FOR ACCURACY.')
330FORMAT(1H0,T20,'THE GIVEN WALL SYSTEM MAY HAVE
EXCESSIVE'/
  1 1H,T20,'MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR OF'/
  2 1H,T20,'SAFETY. PLEASE CHECK INPUT VALUES OF STRUT'/
  3 1H,T20,'SPACING & STIFFNESS AND WALL STIFFNESS FOR'/
  4 1H,T20,'ACCURACY.')
 340 FORMAT(1H0,T20,'THE REQUIRED SYSTEM WOULD BE VERY
FLEXIBLE'/
  1 1H,T20,'AND MAY CAUSE EXCESSIVE MOVEMENTS. PLEASE'/
  2 1H,T20,'VERIFY ALLOWABLE MOVEMENTS.')
 350  FORMAT(1H0,T20,'THE REQUIRED SYSTEM WOULD BE VERY
STIFF'/
  1 1H,T20,'AND EXCEEDS AVAILABLE DATA CURVES. PLEASE'/
  2 1H,T20,'VERIFY ALLOWABLE MOVEMENTS.')
 360  FORMAT(1H0,T20,'THE REQUIRED SYSTEM MAY HAVE
EXCESSIVE'/
  1 1H,T20,'MOVEMENTS DUE TO FLEXIBILITY & LOW FACTOR'/
  2 1H,T20,'OF SAFETY. PLEASE VERIFY ALLOWABLE MOVEMENTS.')
      RETURN
      END
```

```
c.............SUBROUTINE DSTRB..............................
c
      SUBROUTINE DSTRB(m,fs,he,disp,d,dv,dl,fselmn)
      DIMENSION fs(20),d(9,20),dv(9,20),dl(9,20),x(9,20),
     1          y(9,20),z(9,20),f10x(8),f10y(8),f13x(8),
     2          f13y(8),f17x(8), f17y(8),f22x(8),f22y(8),
     3          f24x(8),f24y(8),g10x(9), g10y(9),g15x(9),
     4          g15y(9), disp(20),fselmn(20)
      COMMON de,hw,b,q,io,eln
c
c   ......distrib. of vert. movement.....(fig 3.9)......
c
      DATA g10x/0.0,0.5,1.0,1.5,2.0,2.15,2.5,3.0,3.5/,
     1    g10y/1.0,1.0,1.0,0.575,0.25,0.15,0.125,0.1,0.09/,
     2     g15x/0.0,0.5,1.0,1.5,2.0,2.5,2.9,3.0,3.5/,
     3     g15y/1.0,1.0,0.95,0.75,0.6,0.45,0.325,0.3,0.25/
      n=9
         i=1
         x(i,m)=0.0
         fs1=fselmn(m)
 140     d1=x(i,m)
         CALL COEFS (n,g10x,g10y,d1,d2a)
         CALL COEFS (n,g15x,g15y,d1,d2b)
           IF(fs1.LE.1.00) THEN
             d2=d2a
             GOTO 145
           ENDIF
           IF(fs1.GE.1.50) THEN
             d2=d2b
             GOTO 145
           ENDIF
c..........................................................
c..if 1.0 < fs < 1.5, computes straight line interpolation
   between curves.......
c...........................................................
c
             d2=d2b-(((1.5-fs1)/(0.5))*(d2b-d2a))
c
 145     CONTINUE
         y(i,m)=d2
         d(i,m)=x(i,m)*he
         dv(i,m)=y(i,m)*disp(m)
         j=i+1
         x(j,m)=x(i,m)+0.5
         i=i+1
         IF(i.EQ.9) GOTO 150
         GOTO 140
 150  CONTINUE
c
c  .......distrib. of lateral movement...(fig. 3.10)....
c
```

```
      DATA f10x/0.0,0.5,1.0,1.5,2.0,2.5,3.0,3.5/,
     1     f10y/0.05,0.14,0.35,0.26,0.17,0.1,0.06,0.02/,
     2     f13x/0.0,0.5,1.0,1.5,2.0,2.5,3.0,3.5/,
     3     f13y/0.06,0.18,0.4,0.38,0.26,0.17,0.1,0.06/,
     4     f17x/0.0,0.5,1.0,1.5,2.0,2.5,3.0,3.5/,
     5     f17y/0.15,0.34,0.5,0.43,0.32,0.22,0.14,0.08/,
     6     f22x/0.0,0.5,1.0,1.5,2.0,2.5,3.0,3.5/,
     7     f22y/0.2,0.45,0.71,0.78,0.6,0.44,0.35,0.26/,
     8     f24x/0.0,0.5,1.0,1.5,2.0,2.5,3.0,3.5/,
     9     f24y/0.36,0.72,0.92,0.98,0.94,0.82,0.65,0.5/
c
        i=1
        x(i,m)=0.0
 160    d1=x(i,m)
        IF(fs1.LE.1.05) THEN
           CALL COEFS(n,f10x,f10y,d1,d2)
        ENDIF
c
c  COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN
c        CURVES WHERE FS FALLS IN RANGE: 1.05<FS<=1.3
c
        IF(fs1.GT.1.05.AND.fs1.LE.1.3) THEN
          CALL COEFS(n,f10x,f10y,d1,d2a)
          CALL COEFS(n,f13x,f13y,d1,d2b)
             IF (fs1.EQ.1.3) THEN
             d2=d2b
             GOTO 170
             ENDIF
          d2=d2b-(((1.3-fs1)/(0.25))*(d2b-d2a))
          GOTO 170
        ENDIF
c
c  COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN
c        CURVES WHERE FS FALLS IN RANGE: 1.3<FS<=1.7
c
        IF(fs1.GT.1.3.AND.fs1.LE.1.7) THEN
          CALL COEFS(n,f13x,f13y,d1,d2a)
          CALL COEFS(n,f17x,f17y,d1,d2b)
             IF (fs1.EQ.1.7) THEN
             d2=d2b
             GOTO 170
             ENDIF
          d2=d2b-(((1.3-fs1)/(0.4))*(d2b-d2a))
          GOTO 170
        ENDIF
c
c  COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN
c        CURVES WHERE FS FALLS IN RANGE: 1.7<FS<=2.2
c
        IF(fs1.GT.1.7.AND.fs1.LE.2.2) THEN
          CALL COEFS(n,f17x,f17y,d1,d2a)
```

```
          CALL COEFS(n,f22x,f22y,d1,d2b)
             IF (fs1.EQ.2.2) THEN
             d2=d2b
             GOTO 170
             ENDIF
          d2=d2b-(((2.2-fs1)/(0.5))*(d2b-d2a))
          GOTO 170
        ENDIF
c
c  COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN
c         CURVES WHERE FS>2.2
c
        IF(fs1.GT.2.2) THEN
          CALL COEFS(n,f22x,f22y,d1,d2a)
          CALL COEFS(n,f24x,f24y,d1,d2b)
             IF (fs1.GE.2.4) THEN
             d2=d2b
             GOTO 170
             ENDIF
          d2=d2b-(((2.4-fs1)/(0.2))*(d2b-d2a))
          GOTO 170
        ENDIF
 170  CONTINUE
        z(i,m)=d2
        dl(i,m)=z(i,m)*disp(m)
        j=i+1
        x(j,m)=x(i,m)+0.5
        i=i+1
        IF(i.EQ.9) GOTO 180
        GOTO 160
 180  CONTINUE
c
      WRITE(io,200)
 200  FORMAT(1H0,T15,'Est. Distribution of Ground Surface
        Movement',)
      WRITE(io,210)
 210  FORMAT(1H0,T15,'Dist. fr. Wall',5X,'Vert. Disp.',
        5X,'Lat. Disp.'/)
      DO 250 i=1,8
         WRITE (io,260) d(i,m),dv(i,m),dl(i,m)
 250  CONTINUE
 260  FORMAT(T15,F10.2,T35,F10.4,T49,F10.4)
c
      RETURN
      END
```

```
$DEBUG
c....................SUBROUTINE CHNG
      SUBROUTINE CHNG(mopt,nopt,ei,nstrt,hs,s,title,
     1                nlay,df,gw,dc,gt,h,j,c0,l,dlm,savg,
     2                unit,leng,forc)
      DIMENSION hs(20),l(20),dc(20),gt(20),h(20),j(20),
     1          c0(20),s(20)
      CHARACTER title*72,unit*11,leng*15,forc*15
      COMMON de,hw,b,q,io,eln,CE,CEM,CEH,xks
      IF(nopt.EQ.0) THEN
        dlm = 0
        savg = 0
      ENDIF
      IF(nopt.EQ.1) THEN
        EI = 0
        savg = 0
      ENDIF
      IF(nopt.EQ.2) THEN
        ei = 0
        DO 5 i=1,nstrt
          j(i) = i
          hs(i) = 0
          s(i) = 0
 5      CONTINUE
      ENDIF
      IF(nopt.EQ.3) THEN
        savg = 0
        DO 6 i=1,nstrt
          s(i) = 0
 6      CONTINUE
      ENDIF
c
 10   WRITE(*,20)
 20   FORMAT(//20X,'Change User Options? (yes=1, no=2) '/
     1          20x,'Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 10
      IF (iyn.GT.2) GOTO 10
      IF (iyn.EQ.2) GOTO 40
      WRITE(*,30) mopt
 30   FORMAT(//20x,'MOPT is currently',I2,/
     1          20x,'New MOPT --> '\)
      READ(*,140) mopt
 32   WRITE(*,33) nopt
 33   FORMAT(//20x,'NOPT is currently',I2,/
     1          20x,'New NOPT --> '\)
      READ(*,140) nopt
 40   WRITE(*,50)
 50   FORMAT(//20x,'Change anisotropic strength ratio?'/
     1          20x,'(yes=1, no-2)'/
     1          20x,'Please specify --> '\)
```

```
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 40
      IF (iyn.GT.2) GOTO 40
      IF (iyn.EQ.2) GOTO 70
      WRITE(*,60)
 60   FORMAT(//20x,'New anisotropic strength ratio --> '\)
      READ(*,*) xks
 70   WRITE(*,80)
 80   FORMAT(//20x,'Change cantilever effect data?'/
     1         20x,' (yes=1, no=2)'/
     1         20x,'Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 70
      IF (iyn.GT.2) GOTO 70
      IF (iyn.EQ.2) GOTO 120
      WRITE(*,90)
 90   FORMAT(//20x,'New cantilever effect?'/
     1         20x,' (0=none,1=effect) -->'\)
      READ(*,*) CE
      IF (CE.EQ.0) GOTO 120
      WRITE(*,100)
 100  FORMAT(//20x,'Cantilever Movement at Top -->'\)
      READ(*,*) CEM
      WRITE(*,110)
 110  FORMAT(//20x,'Anticipated Hinge Depth -->'\)
      READ(*,*) CEH
 120  WRITE(*,130)
 130  FORMAT(//20X,'Change soil parameters ?'/
     1         20x,' (yes=1, no=2) '/
     1         20x,'Please specify --> '\)
      READ(*,140) iyn
 140  FORMAT(I2)
      IF (iyn.LT.1) GOTO 120
      IF (iyn.GT.2) GOTO 120
      IF (iyn.EQ.2) GOTO 400
c
 144  WRITE(*,145) nlay
 145  FORMAT(//20x,'Current number of soil layers =',I2/
     1         20x,'Change number of layers? (yes=1,no=2)'/
     2         20x,'Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 144
      IF (iyn.GT.2) GOTO 144
      IF (iyn.EQ.2) GOTO 149
      WRITE(*,146)
 146  FORMAT(//20x,'New number of soil layers = -->')
      READ(*,*) nlay
       DO 147 i=1,nlay
          j(i) = i
          h(i) = 0
          gt(i) = 0
```

```
            c0(i) = 0
            dc(i) = 0
 147  CONTINUE
 149  DO 390 I=1,NLAY
 150  WRITE(*,160) J(I),H(I)
 160  FORMAT(//20X,'Thickness of layer ',I2,' is ',F8.2)
 170  WRITE(*,180)
 180  FORMAT(//20X,' Change layer thickness ?'/
     1          20x,' (yes=1, no=2) '/
     1          20x,' Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 150
      IF (iyn.GT.2) GOTO 150
      IF (iyn.EQ.2) GOTO 210
 190  WRITE(*,200)
 200  FORMAT(//20X,' New layer thickness --> '\)
      READ(*,*) H(I)
c
 210  WRITE(*,220) J(I),GT(I)
 220  FORMAT(//20X,' Unit weight of layer ',I2,' is ',F8.2)
 230  WRITE(*,240)
 240  FORMAT(//20x,' Change unit weight ? (yes=1, no=2) '/
     1          20x,' Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 210
      IF (iyn.GT.2) GOTO 210
      IF (iyn.EQ.2) GOTO 270
 250  WRITE(*,260)
 260  FORMAT(//20x,' New unit weight --> '\)
      READ(*,*) GT(I)
c
 270  WRITE(*,280) J(I),C0(I)
 280  FORMAT(//20x,' Cohesion of layer ',I2,' is ',F8.2)
 290  WRITE(*,300)
 300  FORMAT(//20x,'Change cohesion ? (yes=1, no=2) '/
     1          20x,' Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 270
      IF (iyn.GT.2) GOTO 270
      IF (iyn.EQ.2) GOTO 330
 310  WRITE(*,320)
 320  FORMAT(//20x,' New cohesion --> '\)
      READ(*,*) C0(I)
c
 330  WRITE(*,340) J(I),DC(I)
 340  FORMAT(//20x,' Cohesion increase of layer ',I2,/
     1          20x,' is ',F8.2)
 350  WRITE(*,360)
 360  FORMAT(//20x,' Change cohesion increase ?'/
     1          20x,' (yes=1, no=2) '/
     1          20x,' Please specify --> '\)
```

```
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 330
      IF (iyn.GT.2) GOTO 330
      IF (iyn.EQ.2) GOTO 390
 370  WRITE(*,380)
 380  FORMAT(//20x,' New cohesion increase --> '\)
      READ(*,*) DC(I)
 390  CONTINUE
c
 400  WRITE(*,410)
 410  FORMAT(//20x,' Change firm layer depth ?'/
     1          20x,' (yes=1, no=2) '/
     1          20x,' Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 400
      IF (iyn.GT.2) GOTO 400
      IF (iyn.EQ.2) GOTO 440
 420  WRITE(*,430)
 430  FORMAT(//20x,' New depth to firm layer --> '\)
      READ(*,*) df
 440  WRITE(*,450)
 450  FORMAT(//20x,' Change water table data ?'/
     1          20x,' (yes=1, no=2) '/
     1          20x,' Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 440
      IF (iyn.GT.2) GOTO 440
      IF (iyn.EQ.2) GOTO 480
 460  WRITE(*,470)
 470  FORMAT(//20x,' New unit weight of water --> '\)
      READ(*,*) gw
 480  WRITE(*,490)
 490  FORMAT(//20x,' Change excavation geometry?'/
     1          20x,' (yes=1,no=2) '/
     1          20x,' Please specify --> '\)
      READ(*,140) iyn
      IF (iyn.LT.1) GOTO 480
      IF (iyn.GT.2) GOTO 480
      IF (iyn.EQ.2) GOTO 550
 500  WRITE(*,510)
 510  FORMAT(//20x,' New excavation width --> '\)
      READ(*,*) b
      WRITE(*,520)
 520  FORMAT(//20x,' New excavation length --> '\)
      READ(*,*) eln
      WRITE(*,530)
 530  FORMAT(//20x,' New final excavation depth --> '\)
      READ(*,*) hw
      WRITE(*,540)
 540  FORMAT(//20x,'New surcharge next to excavation--> '\)
      READ(*,*) q
```

```
c
 550  hstrt=0
      IF(nopt.EQ.1) GOTO 630
c
 560  WRITE(*,570) ei
 570  FORMAT(//20X,'Current wall stiffness = ',F12.2/
     1         20x,'Change wall stiffness?  (yes=1, no=2)'/
     2         20X,'  Please specify --> '\)
      READ(*,580) iyn
 580  FORMAT(I2)
      IF(iyn.LT.1) GOTO 560
      IF(iyn.GT.2) GOTO 560
      IF(iyn.EQ.2) GOTO 630
      WRITE(*,590)
 590  FORMAT(//20X,'New wall stiffness --> '\)
      READ(*,*) ei
c
      IF(nopt.EQ.3) GOTO 630
      IF(nopt.EQ.2) THEN
 600  WRITE(*,610) savg
 610  FORMAT(//20X,'Current average strut stiffness =
'F12.2/
     1 20x,'Change average strut stiffness? (yes=1, no=2)'/
     2            20X,'  Please specify --> '\)
         READ(*,580) iyn
         IF(iyn.LT.1) GOTO 560
         IF(iyn.GT.2) GOTO 560
         IF(iyn.EQ.2) GOTO 630
         WRITE(*,620)
 620     FORMAT(//20X,'New average strut stiffness --> '\)
         READ(*,*) savg
         GOTO 770
      ENDIF
c
 630  WRITE(*,640) nstrt
 640  FORMAT(//20X,'Current number of struts = ',I5/
     1      20x,'Change number of struts? (yes=1, no=2)'/
     2      20X,'  Please specify --> '\)
      READ(*,580) iyn
      IF(iyn.LT.1) GOTO 630
      IF(iyn.GT.2) GOTO 630
      IF(iyn.EQ.2) GOTO 670
      WRITE(*,650)
 650  FORMAT(//20X,'New number of struts --> '\)
      READ(*,660) nstrt
 660  FORMAT(I2)
      ms=nstrt
      GOTO 690
c
 670  WRITE(*,680)
 680  FORMAT(//20X,'Change strut spacing?  (yes=1, no=2)'/
```

```
     1          20X,'  Please specify --> '\)
      READ(*,580) iyn
      IF(iyn.LT.1) GOTO 670
      IF(iyn.GT.2) GOTO 670
      IF(iyn.EQ.2) GOTO 720
 690  DO 710 i=1,nstrt
         WRITE(*,700) i
 700     FORMAT(/20X,'New spacing for strut ',I2,' --> '\)
         READ(*,*) hs(i)
         hstrt=hstrt+hs(i)
 710  CONTINUE
      IF(hstrt.GE.hw) GOTO 720
      ms=ms+1
      hs(ms)=hw-hstrt
c
      IF(nopt.EQ.3) GOTO 770
c
 720  WRITE(*,730)
 730  FORMAT(//20X,' Change strut stiffnesses?'/
     1          20x,' (yes=1, no=2)'/
     1          20X,'  Please specify --> '\)
      READ(*,580) iyn
      IF(iyn.LT.1) GOTO 720
      IF(iyn.GT.2) GOTO 720
      IF(iyn.EQ.2) GOTO 770
 740  DO 760 i=1,nstrt
         WRITE(*,750) i
 750   FORMAT(/20X,'New stiffness for strut ',I2,' --> '\)
         READ(*,*) s(i)
 760  CONTINUE
c
c........write data into file......

c
 770  REWIND 5
      WRITE(5,*) title
      WRITE(5,775) unit,leng,forc
 775  FORMAT(1H',A11,1H',1H,,1H',A15,1H',1H,,1H',A15,1H')
      WRITE(5,*) mopt,nopt
      WRITE(5,*) nlay,nstrt,xks
      WRITE(5,*) CE,CEM,CEH
      DO 780 i=1,nlay
         WRITE(5,*) i,h(i),gt(i),c0(i),dc(i)
 780  CONTINUE
      WRITE(5,*) df
      WRITE(5,*) gw
      WRITE(5,*) b,eln,hw,q
c
      IF(nopt.EQ.0) GOTO 790
      IF(nopt.EQ.1) GOTO 820
      IF(nopt.EQ.2) GOTO 830
```

```
      IF(nopt.EQ.3) GOTO 840
c
 790  WRITE(5,*) ei
 800  DO 810 i=1,nstrt
         WRITE(5,*) i,hs(i),s(i)
 810  CONTINUE
      GOTO 860
c
 820  WRITE(5,*) dlm
      GOTO 800
c
 830  WRITE(5,*) dlm
      WRITE(5,*) ei
      WRITE(5,*) savg
c
 840  WRITE(5,*) dlm
      WRITE(5,*) ei
      DO 850 i=1,nstrt
         WRITE(5,*) i,hs(i),s(i)
 850  CONTINUE
c
 860  CLOSE (5)
      RETURN
      END
```

```
c.........................SUBROUTINE COEFS
c
      SUBROUTINE COEFS(n,x,y,a,b)
      DIMENSION x(n),y(n),c(4,4),d(4),work(4),ipvt(4)
c
      IF(a.GT.x(2)) GOTO 1
        x1=x(1)
        x2=x(2)
        x3=x(3)
        x4=x(4)
        y1=y(1)
        y2=y(2)
        y3=y(3)
        y4=y(4)
      GOTO 2
c
 1    n1=n-1
      IF(a.LT.x(n1)) GOTO 5
        x1=x(n-3)
        x2=x(n-2)
        x3=x(n-1)
        x4=x(n)
        y1=y(n-3)
        y2=y(n-2)
        y3=y(n-1)
        y4=y(n)
      GOTO 2
c
 5    n2=n-2
      DO 3 i=2,n2
         IF(a.LT.x(i).OR.a.GT.x(i+1)) GOTO 3
           x1=x(i-1)
           x2=x(i)
           x3=x(i+1)
           x4=x(i+2)
           y1=y(i-1)
           y2=y(i)
           y3=y(i+1)
           y4=y(i+2)
         GOTO 2
 3    CONTINUE
 2    CONTINUE
c
      DO 4 i=1,4
         IF(i.EQ.1) xc=x1
         IF(i.EQ.2) xc=x2
         IF(i.EQ.3) xc=x3
         IF(i.EQ.4) xc=x4
           c(i,1)=xc*xc*xc
           c(i,2)=xc*xc
           c(i,3)=xc
```

```
            c(i,4)=1.0
 4      CONTINUE
c
        CALL DECOMP(4,4,c,cond,ipvt,work)
c
        d(1)=y1
        d(2)=y2
        d(3)=y3
        d(4)=y4
c
        CALL SOLVE(4,4,c,d,ipvt)
c
        b=d(1)*a*a*a+d(2)*a*a+d(3)*a+d(4)
c
        RETURN
        END
c
c.......................SUBROUTINE DECOMP
c
        SUBROUTINE DECOMP(ndim,n,a,cond,ipvt,work)
c
        INTEGER ndim,n
        INTEGER ipvt(n)
        REAL a(ndim,n),cond,work(n)
c
        ipvt(n)=1
        IF(n.EQ.1) GOTO 80
        nm1=n-1
        anorm=0
c
        DO 10 j=1,n
           t=0.0
           DO 5 i=1,n
              t=t+ABS(a(i,j))
 5         CONTINUE
           IF(t.GT.anorm) anorm=t
 10     CONTINUE
c
        DO 35 k=1,nm1
           kp1=k+1
           m=k
           DO 15 i=kp1,n
              IF(ABS(a(i,k)).GT.ABS(a(m,k))) m=i
 15        CONTINUE
           ipvt(k)=m
           IF(m.NE.k) ipvt(n)=-ipvt(n)
           t=a(m,k)
           a(m,k)=a(k,k)
           a(k,k)=t
           IF(t.EQ.0.0) GOTO 35
           DO 20 i=kp1,n
```

```
            a(i,k)=-a(i,k)/t
 20      CONTINUE
         DO 30 j=kp1,n
            t=a(m,j)
            a(m,j)=a(k,j)
            a(k,j)=t
            IF(t.EQ.0.0) GOTO 30
            DO 25 i=kp1,n
               a(i,j)=a(i,j)+a(i,k)*t
 25         CONTINUE
 30      CONTINUE
 35   CONTINUE
c
      DO 50 k=1,n
         t=0.0
         IF(k.EQ.1) GOTO 45
         km1=k-1
         DO 40 i=1,km1
            t=t+a(i,k)*work(i)
 40      CONTINUE
 45      ek=1.0
         IF(t.LT.0.0) ek=-1.0
         IF(a(k,k).EQ.0.0) GOTO 90
         work(k)=-(ek+t)/a(k,k)
 50   CONTINUE
c
      DO 60 kb=1,nm1
         k=n-kb
         t=0.0
         kp1=k+1
         DO 55 i=kp1,n
            t=t+a(i,k)*work(k)
 55      CONTINUE
         work(k)=t
         m=ipvt(k)
         IF(m.EQ.k) GOTO 60
         t=work(m)
         work(m)=work(k)
         work(k)=t
 60   CONTINUE
c
      ynorm=0.0
      DO 65 i=1,n
         ynorm=ynorm+abs(work(i))
 65   CONTINUE
c
      CALL SOLVE(ndim,n,a,work,ipvt)
      znorm=0.0
      DO 70 i=1,n
         znorm=znorm+ABS(work(i))
 70   CONTINUE
```

```
      cond=anorm*znorm/ynorm
      IF(cond.LT.1.0) cond=1.0
      RETURN
 80   cond=1.0
      IF(a(1,1).NE.0.0) RETURN
 90   cond=1.0E+32
c
      RETURN
      END
c
c.........................SUBROUTINE SOLVE
c
      SUBROUTINE SOLVE(ndim,n,a,b,ipvt)
c
      INTEGER ndim,n,ipvt(n)
      REAL a(ndim,n),b(n)
c
      IF(n.EQ.1) GOTO 50
      nm1=n-1
      DO 20 k=1,nm1
         kp1=k+1
         m=ipvt(k)
         t=b(m)
         b(m)=b(k)
         b(k)=t
         DO 10 i=kp1,n
            b(i)=b(i)+a(i,k)*t
 10      CONTINUE
 20   CONTINUE
c
      DO 40 kb=1,nm1
         km1=n-kb
         k=km1+1
         b(k)=b(k)/a(k,k)
         t=-b(k)
         DO 30 i=1,km1
            b(i)=b(i)+a(i,k)*t
 30      CONTINUE
 40   CONTINUE
 50   b(1)=b(1)/a(1,1)
c
      RETURN
      END
```

Appendix E

List of Variables used in MOVEX

## List of Variables in MOVEX

ab = alfa b
ad = alfa d
ak = FS anisotropic/FS isotropic
b = excavation width
b7 = 0.7 * excavation width
bcf = bearing capacity factor
bresis = bearing resistance sum provided by soil layers at or below excavation bottom and at or above failure surface
bs = excavation width/height of excavation
c0(i) = undrained strength of layer 'i'
CE = cantilever effect input value (0 or 1)
CEH = depth to hinge point for computing cantilever movements
CEM = amount of cantilever at top of excavation
d = distance between bottom of excavation and failure surface
d(i,j) = ratio of distance from wall to wall height at distance 'i', stage 'j'
dc(i) = change in shear strength with depth of layer 'i'
de = depth of excavation
df = depth to firm layer
dh = nondimensionalized wall movement
disp(i) = wall movement at stage 'i'
dl = d
dl(i,j) = distribution of lateral ground movement
dlm = maximum allowable displacement
ds = depth to firm layer/height of excavation
dv(i,j) = distribution of vertical ground movement
ei = wall stiffness
eln = excavation length
fdb = depth of failure mechanisam
fin = name of input file
fout = name of output file
fs(i) = factor of safety for stage 'i'
fsel(i) = minimum factor of safety for stage 'i'
fselmn = minimum factor of safety
fsmd = factor of safety at each failure mode checked
gm = average total weight adjacent to excavation
gt(i) = total unit weight of soil layer 'i'
gw = unit weight of water
h(i) = thickness of soil layer 'i'
havg = temporary average strut spacing
hb = distance from ground surface to failure mechanism
hei = incremental height of excavation
hl = portion of soil layer adjacent to excavation
hs(i) = distance between strut 'i' and next higher strut

hside = layer thickness above excavation bottom
hstrt = incremental strut height sum
hsum(j) = incremental soil layer sum
HT = actual depth to failure surface, defined as the smaller of df and htob
ht = incremental layer thickness sum
htob = depth to theoretical failure surface, H plus 0.7B
hw = final height of excavation wall
io = output destination
iopt = ending control option
l(i) = strut number
mopt = movement option
ms = nstrt
nlay = number of soil layers adjacent to and below excavation
nopt = design option
nstrt = number of struts
pe = bearing stress due to weight of soil layers adjacent to excavation, incremental total stress sum
q = surcharge adjacent to excavation
rc = resistance to sliding (from cohesion) provided by layers adjacent to excavation
s(i) = stiffness of strut 'i'
savg = average strut stiffness
shs = temporary strut spacing sum
sss = temporary strut stiffness sum
stf = nondimensionalized strut stiffness sum
sub = average of subt and subb
subb = undrained shear strength of layer j, where 'bottom' is at or above failure surface
subt = undrained shear strength of layer j at top of layer, where 'top' is at or below excavation bottom
systf = nondimensionalized strut stiffness
t(j) = thickness of layer j, portion of layer below excavation bottom only
Tfail = distance form excavation bottom to failure surface
title = any identifying title
tsum = sum of layer thicknesses below excavation bottom
wt = depth to water table
x(i,j) = distance 'i' from the wall at stage 'j'
xks = anisotropic strength ratio
y(i,j) = ratio of vertical ground movement to maximum movement at distance 'i' from wall at stage 'j'
z(i,j) = ratio of lateral ground movement to maximum movement at distance 'i' from wall at stage 'j'
akx, aky }--coordinates of ak in Figure 4.4

fsx10
fsy10}--coordinates of FS = 1.0 curve in Figure 2.7
fsx11
fsy11}--coordinates of FS = 1.1 curve in Figure 2.7
fsx14
fsy14}--coordinates of FS = 1.4 curve in Figure 2.7
fsx20
fsy20}--coordinates of FS = 2.0 curve in Figure 2.7
fsx30
fsy30}--coordinates of FS = 3.0 curve in Figure 2.7
fsx10a
fsy10a}-inverted coordinates of FS = 1.0 curve, Fig 2.7
fsx11a
fsy11a}-inverted coordinates of FS = 1.1 curve, Fig 2.7
fsx14a
fsy14a}-inverted coordinates of FS = 1.4 curve, Fig 2.7
fsx20a
fsy20a}-inverted coordinates of FS = 2.0 curve, Fig 2.7
fsx30a
fsy30a}-inverted coordinates of FS = 3.0 curve, Fig 2.7
asx
asy}--coordinates of alfa - s curve (Mana & Clough)
asxa
asya}--inverted coordinates of alfa - s curve
adx
ady}--coordinates of alfa - d curve (Mana & Clough)
abx
aby}--coordinates of alfa - b curve (Mana & Clough)
g10x
g10y}--coordinates of FS = 1.0 in Figure 2.10
g15x
g15y}--coordinates of FS = 1.5 in Figure 2.10
f10x
f10y}--coordinates of FS = 1.0 in Figure 2.11
f13x
g13y}--coordinates of FS = 1.3 in Figure 2.11
f17x
f17y}--coordinates of FS = 1.7 in Figure 2.11
f22x
f22y}--coordinates of FS = 2.2 in Figure 2.11
f24x
f24y}--coordinates of FS = 2.4 in Figure 2.11

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