MOVEX: INTERACTIVE DESIGN OF BRACED EXCAVATIONS
TO LIMIT GROUND MOVEMENTS

by

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MOVEX: Interactive Design of Braced Excavations to Limit Ground Movements

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

(a) $D < B^{(0.7)}$

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

(b) $D > B^{(0.7)}$

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

$$N_C = 5 \left(1 + 0.2 \frac{B}{L}\right) \left(1 + 0.2 \frac{D}{B}\right) \quad (2.1)$$

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

$$N_C = 5 \left(1 + 0.2 \frac{B}{L}\right) \quad (2.2)$$

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 $= \frac{\mu}{H} \frac{S_u N_c}{\gamma}$

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

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

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
\[ F = \frac{N_c \text{Sub} T}{(\gamma H + q)T - \text{SusH}} \]

If \( D < 0.7B \), \( T = D \)
If \( D \geq 0.7B \), \( T = 0.7B \)

- \( \text{Sub} \) = average \( Su \) below excavation
- \( \text{Sus} \) = 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)
Firm

\[ F = \frac{Nc \cdot \sum (\text{Sub} \cdot t)}{[\sum (\gamma \cdot h) + q]T - \sum (\text{Sus} \cdot h)} \]

If D $\geq$ 0.7B, T = D  
If D $>$ 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
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>
<thead>
<tr>
<th></th>
<th>Major Factors Affecting Movements of Supported Excavations (from Clough, 1985)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Excavation depth</td>
</tr>
<tr>
<td>2.</td>
<td>Excavation geometry - width, shape, berms, symmetry</td>
</tr>
<tr>
<td>3.</td>
<td>Duration of excavation</td>
</tr>
<tr>
<td>4.</td>
<td>Construction within excavation</td>
</tr>
<tr>
<td>5.</td>
<td>Wall stiffness</td>
</tr>
<tr>
<td>6.</td>
<td>Tie-back or brace stiffness</td>
</tr>
<tr>
<td>7.</td>
<td>Support spacing</td>
</tr>
<tr>
<td>8.</td>
<td>Type of support connections</td>
</tr>
<tr>
<td>9.</td>
<td>Amount of preload</td>
</tr>
<tr>
<td>10.</td>
<td>Preload maintenance procedures</td>
</tr>
<tr>
<td>11.</td>
<td>Soil strength, sensitivity, and stiffness</td>
</tr>
<tr>
<td>12.</td>
<td>Soil stratification</td>
</tr>
<tr>
<td>13.</td>
<td>Soil property variation with loading direction</td>
</tr>
<tr>
<td>14.</td>
<td>Presence or absence of rigid base below soil strata</td>
</tr>
<tr>
<td>15.</td>
<td>Initial groundwater level</td>
</tr>
<tr>
<td>16.</td>
<td>Groundwater control system</td>
</tr>
<tr>
<td>17.</td>
<td>Wall permeability</td>
</tr>
<tr>
<td>18.</td>
<td>Potential of ground water movement</td>
</tr>
<tr>
<td>19.</td>
<td>Support system construction sequence</td>
</tr>
<tr>
<td>20.</td>
<td>Wall installation technique</td>
</tr>
<tr>
<td>21.</td>
<td>Surcharge behind wall</td>
</tr>
<tr>
<td>22.</td>
<td>Quality of workmanship</td>
</tr>
<tr>
<td>23.</td>
<td>Weather</td>
</tr>
<tr>
<td>24.</td>
<td>Site topography</td>
</tr>
<tr>
<td>25.</td>
<td>Consolidation due to dewatering</td>
</tr>
</tbody>
</table>
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

\[
E = \text{modulus of elasticity of the wall} \\
I = \text{moment of inertia of the wall} \\
\gamma_w = \text{unit weight of water} \\
havg = \text{average strut spacing.}
\]

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

\[
K_I = \frac{A}{E} \cdot \frac{E}{L}
\]

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)

<table>
<thead>
<tr>
<th>Alpha Factor</th>
<th>Approximate Range of Values</th>
<th>Parameter of Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_S$</td>
<td>0.75-1.2</td>
<td>strut stiffness &amp; spacing</td>
</tr>
<tr>
<td>$\alpha_D$</td>
<td>0.62-1.0</td>
<td>depth to firm layer</td>
</tr>
<tr>
<td>$\alpha_B$</td>
<td>1.0-1.8</td>
<td>excavation width</td>
</tr>
</tbody>
</table>
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

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

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 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:

\[ S_u = \gamma_h \tan \phi \]  

where \( S_u \) = "equivalent cohesion" of the sand layer  
\( \gamma_h \) = horizontal effective stress in the sand layer  
\( \phi \) = angle of internal friction of the sand layer

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

\[ S_u = \gamma_v (1-\sin\phi)(\tan\phi) \]  

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)

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

\[
FS = \frac{N_C \; \Lambda_t (\text{Sub} \cdot t)}{\Lambda_t (\alpha \cdot h)T - \Lambda_t (S_{us} \cdot h)}
\]

For comparison with MOVEX, calculate \( N_C \) by equation 2.2.

\[
N_C = 5 \; (1 + 0.2 \; (\text{B/L}))
\]
\[
= 5 \; (1 + 0.2 \; (12/17.1))
\]
\[
= 5.7
\]

At 9m:

Check Depth to Failure Surface:

\[
H + 0.7B = 9 + 8.4 = 17.4m \quad \text{--- Governs}
\]

Depth to firm layer = 30m

\[
T = 8.4m
\]

\[
\text{Sub} = \frac{S_u(@9m) + S_u(@9+0.7B)}{2} = \frac{S_u(@9m) + S_u(@17.4m)}{2}
\]

\[
S_u(@9m) = 28.4 + 2.04(9) = 46.8 \text{ kPa}
\]

\[
S_u(@17.4m) = 28.4 + 2.04(17.4) = 63.9 \text{ kPa}
\]

\[
\text{Sub} = (46.8 + 63.9)/2 = 55.5 \text{ kPa}
\]

\[
S_{us} = S_u(@4.5m)
\]
\[
= 28.4 + 2.04(4.5)
\]
\[
= 37.6 \text{ kPa}
\]

\[
5.7 \; (55.5 \times 8.4)
\]

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

\[
FS = 2.26
\]

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 \(0.7B + H\)

\(T = 15 + 8.4 = 23.4\)

\[
\text{Sub} = \frac{[S_u(@15m) + S_u(@15 + 0.7B)]}{2} = \frac{[S_u(@15m) + S_u(@23.4)]}{2}
\]

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

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

\(\text{Sub} = \frac{(59 + 76.1)}{2} = 67.6 \text{ kPa}\)

\[S_{us} = S_u(@7.5m)\]

\[= 28.4 + 2.04(7.5) = 43.7 \text{ kPa}\]

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

\(FS = 1.74\)

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

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Depth to firm layer from ground surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.00</td>
<td>28.40</td>
<td>30.000</td>
</tr>
<tr>
<td>Unit Weight</td>
<td>20.00</td>
<td>Coh. Increase 2.04</td>
</tr>
</tbody>
</table>

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

<table>
<thead>
<tr>
<th>Total width of excavation</th>
<th>12.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length of excavation</td>
<td>17.10</td>
</tr>
<tr>
<td>Final depth of excavation</td>
<td>15.00</td>
</tr>
<tr>
<td>Surcharge next to excavation</td>
<td>.00</td>
</tr>
<tr>
<td>Wall Stiffness (EI)</td>
<td>.793E+05</td>
</tr>
</tbody>
</table>

STRUT DATA

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.00</td>
<td>.1960E+05</td>
</tr>
<tr>
<td>2</td>
<td>5.50</td>
<td>.1960E+05</td>
</tr>
<tr>
<td>3</td>
<td>9.00</td>
<td>.1960E+05</td>
</tr>
<tr>
<td>4</td>
<td>12.50</td>
<td>.1960E+05</td>
</tr>
</tbody>
</table>
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 = 0.96

Lateral Wall Movement at this Stage is 0.064
Overall Maximum Lateral Wall Movement is 0.064

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 0.090
Overall Maximum Lateral Wall Movement is 0.090
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Layer 1 (0-20 ft.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>$\gamma$</td>
<td>110</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$</td>
<td>0</td>
</tr>
<tr>
<td>Soil Layer 2 (20-40 ft.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>$\gamma$</td>
<td>125</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$</td>
<td>600</td>
</tr>
<tr>
<td>Soil Layer 3 (40-60 ft.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>$\gamma$</td>
<td>125</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$</td>
<td>700</td>
</tr>
<tr>
<td>Soil Layer 4 (60-80 ft)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>$\gamma$</td>
<td>125</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$</td>
<td>1500</td>
</tr>
<tr>
<td>Wall Stiffness (psf/ft)</td>
<td>$EI$</td>
<td>$3.8 \times 10^7$</td>
</tr>
<tr>
<td>Strut Stiffness (psf/ft)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strut 1 (at 4 ft)</td>
<td>$AE/L$</td>
<td>508</td>
</tr>
<tr>
<td>Strut 2 (at 12 ft)</td>
<td>$AE/L$</td>
<td>$1.11 \times 10^6$</td>
</tr>
<tr>
<td>Strut 3 (at 24 ft)</td>
<td>$AE/L$</td>
<td>$1.59 \times 10^6$</td>
</tr>
<tr>
<td>Excavation Width (ft)</td>
<td>$B$</td>
<td>230</td>
</tr>
<tr>
<td>Excavation Length (ft)</td>
<td>$L$</td>
<td>440</td>
</tr>
<tr>
<td>Final Excavation Depth (ft)</td>
<td>$D$</td>
<td>29</td>
</tr>
<tr>
<td>Depth to Firm Layer (ft)</td>
<td>$\gamma_w$</td>
<td>80</td>
</tr>
<tr>
<td>Surcharge Next to Excavation (psf)</td>
<td>$q$</td>
<td>650</td>
</tr>
</tbody>
</table>
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.

\[
FS = \frac{N_C \frac{\Delta f}{(S_{ub} \cdot t)}}{\Delta f((\gamma \cdot h)T - \Delta f(S_{ush} \cdot h))}
\]

Calculate \(N_C\) by equation 2.2.

\[
N_C = 5 \left(1 + 0.2 \frac{(B/L)}{}ight)
\]

\[
= 5 \left(1 + 0.2 \left(\frac{230}{440}\right)\right)
\]

\[
= 5.52
\]

Check depth to failure surface:

\[H + 0.7B = 29 + 161 = 190 \text{ ft.}\]

Depth to firm layer = 80 ft. \( \text{———Governs}\)

\[T = 80 - 29 = 51 \text{ ft.}\]

At 29 feet:

layer 1: \(S_u = 0, \ \gamma = 110, \ d = 20; \ S_{ush} = 0 \ \gamma h = 2200\)

layer 2: \(S_u = 600, \ \gamma = 125, \ h = 9; \ S_{ush} = 5400 \ \gamma h = 1125\)

\[\Delta_f S_{ush} = 5400 \ \Delta_f \gamma h = 3325\]

\[q = 650\]

Below Excavation Bottom:

layer 2: \(S_{ub} = 600 \ \ t = 11\) \(S_{ubt} = 6600\)

layer 3: \(S_{ub} = 700 \ \ t = 20\) \(S_{ubt} = 14000\)

layer 4: \(S_{ub} = 1500 \ \ t = 20\) \(S_{ubt} = 30000\)

\[\Delta_f S_{ubt} = 50600\]

5.52 (50600)

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

\[FS = 1.42\]

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

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Unit Weight</th>
<th>Cohesion</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
<td>110.00</td>
<td>.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 2

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Unit Weight</th>
<th>Cohesion</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
<td>125.00</td>
<td>600.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 3

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Unit Weight</th>
<th>Cohesion</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
<td>125.00</td>
<td>700.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 4

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Unit Weight</th>
<th>Cohesion</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
<td>125.00</td>
<td>1500.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.00</td>
<td>.5080E+03</td>
</tr>
<tr>
<td>2</td>
<td>12.00</td>
<td>.1110E+07</td>
</tr>
<tr>
<td>3</td>
<td>24.00</td>
<td>.1590E+07</td>
</tr>
</tbody>
</table>

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
Brace Levels

Stage 1
Stage 2
Stage 3
Stage 4

□ — Maximum
Predicted by
MOVEX

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 ($\delta_M$):

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

At 9m:

(d = 9m)
FS = 2.3 (from Example 3.4.1)

from Figure 2.7,

$\delta_M/d = 0.4\%$

$\delta_M = 0.004(9) = 0.036m$

At 15m:

(d = 15m)

FS = 1.7 (from Example 3.4.1)

from Figure 2.7,

$\delta_M/d = 0.6\%$

$\delta_M = 0.006(15) = 0.090m$

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.

$\delta_V$

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 $\delta_V = 0.090(0.975) = 0.088m$
From Figure 2.11, 
\[ \frac{\delta L_s}{\delta M} = 0.5 \]
\[ \delta L_s = 0.5 (0.090) = 0.045 \text{m} \]

From the following printout, MOVEX gives \( \delta V = 0.0896 \text{m} \) and \( \delta L_s = 0.0461 \text{m} \). 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

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.00</td>
<td>28.40</td>
<td>20.00</td>
<td>2.04</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.00</td>
<td>.1960E+05</td>
</tr>
<tr>
<td>2</td>
<td>5.50</td>
<td>.1960E+05</td>
</tr>
<tr>
<td>3</td>
<td>9.00</td>
<td>.1960E+05</td>
</tr>
<tr>
<td>4</td>
<td>12.50</td>
<td>.1960E+05</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td>3.00</td>
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<td>4.00</td>
<td>0.0038</td>
<td>0.0059</td>
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<tr>
<td>5.00</td>
<td>0.0028</td>
<td>0.0052</td>
</tr>
<tr>
<td>6.00</td>
<td>0.0019</td>
<td>0.0041</td>
</tr>
<tr>
<td>7.00</td>
<td>0.0016</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
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<tbody>
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<td>.00</td>
<td>.0151</td>
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<tr>
<td>19.25</td>
<td>.0038</td>
<td>.0075</td>
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</table>

**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

<table>
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**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

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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

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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 ($\phi = 0^\circ$). 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 ($\beta > 0^\circ$). If the principal stresses rotate as much as $90^\circ$, 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 accommodation 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

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

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

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:

$$FS = \frac{1}{H} \frac{N_c^* S_{u0}}{\gamma - \frac{0.5S_{u0}(1+K_s)}{0.7B}}$$  \hspace{1cm} (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
Undrained Strength Anisotropy versus Plasticity Index for Normally Consolidated Clays

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,

\[ \text{FS} = \frac{N_c \xi (S_{ub} \cdot t)}{[ \xi (\tau \cdot h) + q] T - \xi (S_{us} \cdot h)} \]  

(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 \( K_s \) 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

\[ FS(\text{anisotropic}) = "ak" \times FS(\text{isotropic}) \]

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

\[ FS = 0.75 \times 2.26 = 1.7 \]

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

\[ FS = 0.75 \times 1.74 = 1.3 \]

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

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CANTILEVER EFFECT

No Cantilever Movements are Anticipated

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Depth to firm layer from ground surface 30.000

WATER TABLE DATA

Unit weight of water 9.81

EXCAVATION GEOMETRY

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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

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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

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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

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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 0.095
Overall Maximum Lateral Wall Movement is 0.095

Est. Distribution of Ground Surface Movement

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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 0.134
Overall Maximum Lateral Wall Movement is 0.134

Est. Distribution of Ground Surface Movement

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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
Wall Profile with Cantilever Movement

Cantilever Movement

Hinge Point

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
Observed Profiles of Phases I and II Walls

Figure 5.3 - Trends of Similar Walls with and without Cantilever Movements (after Clough and Davidson, 1977)
Profile of Phase II Wall with 6cm Cantilever Movement Removed shown with Final Phase I Wall Profile

Lateral Wall Deflection (cm)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubble Fill (0-7.5m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>$\gamma$</td>
<td>14.4</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_{u0}$</td>
<td>20</td>
</tr>
<tr>
<td>Soft Clay (7.5-30m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>$\gamma$</td>
<td>15.7</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_{u0}$</td>
<td>24.5+1.3l</td>
</tr>
<tr>
<td>Sand (30-45m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Angle of Internal Friction (degrees)</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Equivalent Shear Strength (kPa)</td>
<td>$S_{u0}$</td>
<td>79</td>
</tr>
<tr>
<td>Wall Stiffness (kPa/m)</td>
<td>$EI$</td>
<td>$6.01 \times 10^4$</td>
</tr>
<tr>
<td>Strut Stiffness (kPa/m)</td>
<td>$AE/L$</td>
<td>$3.53 \times 10^5$</td>
</tr>
<tr>
<td>Number of Strut Levels</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Vertical Strut Spacing (m)</td>
<td>5, 3, 3.5</td>
<td></td>
</tr>
<tr>
<td>Excavation Width (m)</td>
<td>$B$</td>
<td>41.25</td>
</tr>
<tr>
<td>Final Excavation Depth (m)</td>
<td>$D$</td>
<td>13.8</td>
</tr>
<tr>
<td>Excavation Length (m)</td>
<td>$L$</td>
<td>82.5</td>
</tr>
<tr>
<td>Depth to Firm Layer (m)</td>
<td></td>
<td>100.0</td>
</tr>
<tr>
<td>Unit Weight of Water (kPa/m)</td>
<td>$\gamma_w$</td>
<td>9.81</td>
</tr>
</tbody>
</table>
MOVEX Predicted Profiles of Phase II Wall with Varying Cantilever Movements

Figure 5.5: Predicted Wall Movements for Given Amounts of Cantilever Movement
Comparison of Phase II Wall Movements
Observed versus MOVEX Predictions

Lateral Displacement (cm)

Figure 5.6 - Observed versus Predicted Wall Movements for Equal Cantilever Movements
Comparison of Observed Wall Movements for Phases I & II with MOVEX Predicted Movements for Phase II

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

<table>
<thead>
<tr>
<th>Thickness</th>
<th>7.50</th>
<th>Cohesion</th>
<th>20.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>14.40</td>
<td>Coh. Increase</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 2

<table>
<thead>
<tr>
<th>Thickness</th>
<th>22.50</th>
<th>Cohesion</th>
<th>24.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>15.70</td>
<td>Coh. Increase</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Layer number 3

<table>
<thead>
<tr>
<th>Thickness</th>
<th>15.00</th>
<th>Cohesion</th>
<th>79.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>20.00</td>
<td>Coh. Increase</td>
<td>.00</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>.3530E+06</td>
</tr>
<tr>
<td>2</td>
<td>8.00</td>
<td>.3530E+06</td>
</tr>
<tr>
<td>3</td>
<td>11.20</td>
<td>.3530E+06</td>
</tr>
</tbody>
</table>

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 = 0.75

Lateral Wall Movement at this Stage is 0.068
Overall Maximum Lateral Wall Movement is 0.068

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 = 0.75

Lateral Wall Movement at this Stage is 0.097
Overall Maximum Lateral Wall Movement is 0.097
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

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.50</td>
<td>20.00</td>
<td>14.40</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 2

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.50</td>
<td>24.50</td>
<td>15.70</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Layer number 3

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.00</td>
<td>79.00</td>
<td>20.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

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) \( \cdot 601E+05 \)

**STRUT DATA**

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>.3530E+06</td>
</tr>
<tr>
<td>2</td>
<td>8.00</td>
<td>.3530E+06</td>
</tr>
<tr>
<td>3</td>
<td>11.20</td>
<td>.3530E+06</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.50</td>
<td>20.00</td>
<td>14.40</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 2

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.50</td>
<td>24.50</td>
<td>15.70</td>
<td>1.31</td>
</tr>
</tbody>
</table>

Layer number 3

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.00</td>
<td>79.00</td>
<td>20.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

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) = 0.601E+05

STRUT DATA

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>0.3530E+06</td>
</tr>
<tr>
<td>2</td>
<td>8.00</td>
<td>0.3530E+06</td>
</tr>
<tr>
<td>3</td>
<td>11.20</td>
<td>0.3530E+06</td>
</tr>
</tbody>
</table>

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 = 0.75

Lateral Wall Movement at this Stage is 0.015
Cantilever Movement at this Stage is 0.035
Total Wall Movement at this Stage is 0.050
Overall Maximum Lateral Wall Movement is 0.050

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 = 0.75

Lateral Wall Movement at this Stage is 0.035
Cantilever Movement at this Stage is 0.031
Total Wall Movement at this Stage is 0.066
Overall Maximum Lateral Wall Movement is 0.066

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 case 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

<table>
<thead>
<tr>
<th>Case</th>
<th>Support System</th>
</tr>
</thead>
</table>
| 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 VII) 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fill Layer (0-5 ft)</strong></td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>$\gamma$</td>
<td>125</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$</td>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>800</td>
</tr>
<tr>
<td><strong>Clay Layer 2 (10-59 ft)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>$\gamma$</td>
<td>120</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$(low)</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>900</td>
</tr>
<tr>
<td><strong>Clay Layer 3 (59-72 ft)</strong></td>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
<td></td>
<td>$S_u$(high)</td>
<td>6000</td>
</tr>
<tr>
<td><strong>Wall Stiffness (psf/ft)</strong></td>
<td>EI</td>
<td>$3.8 \times 10^7$</td>
</tr>
<tr>
<td><strong>Strut Stiffness (psf/ft)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strut 1 (at 9 ft)</td>
<td>$AE/L$</td>
<td>$6.48 \times 10^5$</td>
</tr>
<tr>
<td>Strut 2 (at 25 ft)</td>
<td>$AE/L$</td>
<td>$8.08 \times 10^5$</td>
</tr>
<tr>
<td><strong>Excavation Width (ft)</strong></td>
<td>B</td>
<td>185</td>
</tr>
<tr>
<td><strong>Excavation Length (ft)</strong></td>
<td>L</td>
<td>150</td>
</tr>
<tr>
<td><strong>Final Excavation Depth (ft)</strong></td>
<td>D</td>
<td>30</td>
</tr>
<tr>
<td><strong>Depth to Firm Layer (ft)</strong></td>
<td>D</td>
<td>59</td>
</tr>
<tr>
<td><strong>Surcharge Next to Excavation (psf)</strong></td>
<td>q</td>
<td>100</td>
</tr>
<tr>
<td><strong>Cantilever Movement Top of Wall (ft)</strong></td>
<td>CEM</td>
<td>0.083</td>
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<tr>
<td><strong>Cantilever Hinge Depth (ft)</strong></td>
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</tr>
<tr>
<td><strong>Unit Weight of Water (pcf)</strong></td>
<td>$\gamma_w$</td>
<td>62.4</td>
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</table>
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
Case 1: One Financial Place, Chicago

Observed and Predicted Wall Movements versus Depth

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

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<thead>
<tr>
<th>Parameter</th>
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<th>Value</th>
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<td><strong>Fill Layer (0-10 ft)</strong></td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>( \gamma' )</td>
<td>120</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>( S_u )</td>
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</tr>
<tr>
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<td>( \gamma' )</td>
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<td>( S_u(\text{low}) )</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>( S_u(\text{high}) )</td>
<td>800</td>
</tr>
<tr>
<td><strong>Clay Layer 2 (48.5-81 ft)</strong></td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>( \gamma' )</td>
<td>110</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>( S_u(\text{low}) )</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>( S_u(\text{high}) )</td>
<td>2000</td>
</tr>
<tr>
<td><strong>Wall Stiffness (psf/ft)</strong></td>
<td>( E_I )</td>
<td>( 1.36 \times 10^7 )</td>
</tr>
<tr>
<td><strong>Strut Stiffness (psf/ft)</strong></td>
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<td></td>
</tr>
<tr>
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<td>( A_E/L )</td>
<td>( 1.41 \times 10^6 )</td>
</tr>
<tr>
<td>Strut 2 (at 14 ft)</td>
<td>( A_E/L )</td>
<td>( 2.09 \times 10^6 )</td>
</tr>
<tr>
<td>Strut 3 (at 25 ft)</td>
<td>( A_E/L )</td>
<td>( 2.09 \times 10^5 )</td>
</tr>
<tr>
<td><strong>Excavation Width (ft)</strong></td>
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</tr>
<tr>
<td><strong>Excavation Length (ft)</strong></td>
<td>( L )</td>
<td>210</td>
</tr>
<tr>
<td><strong>Final Excavation Depth (ft)</strong></td>
<td>( D )</td>
<td>32.5</td>
</tr>
<tr>
<td><strong>Depth to Firm Layer (ft)</strong></td>
<td>( D )</td>
<td>48.5</td>
</tr>
<tr>
<td><strong>Surcharge Next to Excavation (psf)</strong></td>
<td>( q )</td>
<td>100</td>
</tr>
<tr>
<td><strong>Cantilever Movement Top of Wall (ft)</strong></td>
<td>( C_{EM} )</td>
<td>0.33</td>
</tr>
<tr>
<td><strong>Cantilever Hinge Depth (ft)</strong></td>
<td>( C_{EH} )</td>
<td>45</td>
</tr>
<tr>
<td><strong>Unit Weight of Water (pcf)</strong></td>
<td>( \gamma_w )</td>
<td>62.4</td>
</tr>
</tbody>
</table>
Case 2: Quaker Tower Project, Chicago

Observed and Predicted Movements versus Depth

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

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<tr>
<th>Parameter</th>
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<th>Value</th>
</tr>
</thead>
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<td>Fill Layer (0-20 ft)</td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
<td>γ</td>
<td>110</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$</td>
<td>0</td>
</tr>
<tr>
<td>Clay Layer 1 (20-40 ft)</td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
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<td>125</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$(low)</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>800</td>
</tr>
<tr>
<td>Clay Layer 2 (40-60 ft)</td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
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<td>125</td>
</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$(low)</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>1000</td>
</tr>
<tr>
<td>Clay Layer 3 (60-80 ft)</td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (pcf)</td>
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</tr>
<tr>
<td>Undrained Shear Strength (psf)</td>
<td>$S_u$(low)</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>2000</td>
</tr>
<tr>
<td>Wall Stiffness (psf/ft)</td>
<td>EI</td>
<td>$3.8 \times 10^7$</td>
</tr>
<tr>
<td>Strut Stiffness (psf/ft)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strut 1 (at 4 ft)</td>
<td>AE/L</td>
<td>$5.08 \times 10^2$</td>
</tr>
<tr>
<td>Strut 2 (at 12 ft)</td>
<td>AE/L</td>
<td>$1.11 \times 10^6$</td>
</tr>
<tr>
<td>Strut 3 (at 24 ft)</td>
<td>AE/L</td>
<td>$1.59 \times 10^6$</td>
</tr>
<tr>
<td>Excavation Width (ft)</td>
<td>B</td>
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<tr>
<td>Excavation Length (ft)</td>
<td>L</td>
<td>440</td>
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<td>Final Excavation Depth (ft)</td>
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</tr>
<tr>
<td>Depth to Firm Layer (ft)</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Surcharge Next to Excavation (psf)</td>
<td>q</td>
<td>650</td>
</tr>
<tr>
<td>Cantilever Movement Top of Wall (ft)</td>
<td>CEM</td>
<td>0.083</td>
</tr>
<tr>
<td>Cantilever Hinge Depth (ft)</td>
<td>CEH</td>
<td>30</td>
</tr>
<tr>
<td>Unit Weight of Water (pcf)</td>
<td>$\gamma_w$</td>
<td>62.4</td>
</tr>
</tbody>
</table>
Case 3: 900 North Michigan Ave., Chicago
Observed and Predicted Movements versus Depth

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 \( S_u(\text{low}) \), and the laboratory values given in Broms, et al (1986) and Wong (1987) are termed \( S_u(\text{avg}) \). The high values of shear strength used in the MOVEX analyses are derived from the larger of \( S_u(\text{low}) \) and \( S_u(\text{avg}) \). 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 \( S_u(\text{high}) \) may have the value of \( S_u(\text{avg}) \) at the top of the layer and \( S_u(\text{low}) \) 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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td><strong>Fill Layer (0-1m)</strong></td>
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<td>Total Unit Weight (kPa/m)</td>
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</tr>
<tr>
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<td>$S_u$(high)</td>
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</tr>
<tr>
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<td>$S_u$(high)</td>
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</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
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</tr>
<tr>
<td><strong>Lower Marine Clay Layer (26-33m)</strong></td>
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<tr>
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</tr>
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</tr>
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Table 6.6

<table>
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<th>$S_u$</th>
<th>$\sigma'_v$</th>
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<td>4</td>
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<td>18</td>
<td>40-80</td>
<td>183</td>
<td>40</td>
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<td></td>
<td>34</td>
<td></td>
<td></td>
<td>240</td>
<td>53</td>
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<table>
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<th>$S_u$(avg)</th>
<th>$S_u$(high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>0 + 4h</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Upper Clay</td>
<td>4 + 1.4h</td>
<td>30</td>
<td>20 + 0.8h</td>
</tr>
<tr>
<td>Lower Clay</td>
<td>40 + 1.9h</td>
<td>60</td>
<td>40 + 5.7h</td>
</tr>
</tbody>
</table>

Sand: $C_{eq} = "Equivalence Cohesion" = \sigma'_v K_0 \tan \phi$, and
$\phi = 30^\circ, K_0 = 0.9$, 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
Project A: Telecom Building, Singapore

Observed and Predicted Movements versus Depth

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill Layer (0-2m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>( \gamma )</td>
<td>15</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>( S_u(\text{low}) )</td>
<td>0+2.2h</td>
</tr>
<tr>
<td></td>
<td>( S_u(\text{high}) )</td>
<td>10</td>
</tr>
<tr>
<td>Upper Marine Clay Layer (2-5m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>( \gamma )</td>
<td>14</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>( S_u(\text{low}) )</td>
<td>4.4+0.9h</td>
</tr>
<tr>
<td></td>
<td>( S_u(\text{high}) )</td>
<td>10</td>
</tr>
<tr>
<td>Sand Layer (5-6.5m)</td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>( \gamma )</td>
<td>17</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>( S_u )</td>
<td>10</td>
</tr>
<tr>
<td>Lower Marine Clay Layer (6.6-14m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>( \gamma )</td>
<td>15</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>( S_u(\text{low}) )</td>
<td>10+1.1h</td>
</tr>
<tr>
<td></td>
<td>( S_u(\text{high}) )</td>
<td>10+1.1h</td>
</tr>
<tr>
<td>Stiff Sandy Silt (14-34m)</td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>( \gamma )</td>
<td>18.5</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>( S_u )</td>
<td>70</td>
</tr>
<tr>
<td>Wall Stiffness (kPa/m)</td>
<td>( EI )</td>
<td>2.34 \times 10^4</td>
</tr>
<tr>
<td>Strut Stiffness (kPa/m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strut 1 (at 1m)</td>
<td>( AE/L )</td>
<td>9.97 \times 10^4</td>
</tr>
<tr>
<td>Strut 2 (at 3m)</td>
<td>( AE/L )</td>
<td>9.97 \times 10^4</td>
</tr>
<tr>
<td>Strut 3 (at 5.5m)</td>
<td>( AE/L )</td>
<td>1.22 \times 10^5</td>
</tr>
<tr>
<td>Strut 4 (at 7.5m)</td>
<td>( AE/L )</td>
<td>1.22 \times 10^5</td>
</tr>
<tr>
<td>Strut 5 (at 9.5m)</td>
<td>( AE/L )</td>
<td>1.22 \times 10^5</td>
</tr>
<tr>
<td>Strut 6 (at 11.8m)</td>
<td>( AE/L )</td>
<td>1.22 \times 10^5</td>
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<td>Excavation Width (m)</td>
<td>( B )</td>
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</tr>
<tr>
<td>Excavation Length (m)</td>
<td>( L )</td>
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<td>Depth to Firm Layer (m)</td>
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<td>14</td>
</tr>
<tr>
<td>Surcharge Next to Excavation (kPa)</td>
<td>q</td>
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</tr>
<tr>
<td>Cantilever Movement Top of Wall (m)</td>
<td>CEM</td>
<td>0.1</td>
</tr>
<tr>
<td>Cantilever Hinge Depth (m)</td>
<td>CEH</td>
<td>30</td>
</tr>
<tr>
<td>Unit Weight of Water (kPa/m)</td>
<td>$\gamma_w$</td>
<td>9.81</td>
</tr>
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</table>
Table 6.8
Evaluation of Shear Strength Ranges for Case B

<table>
<thead>
<tr>
<th>Layer</th>
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<th>$\gamma$</th>
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<th>$\phi'$</th>
<th>$S_u$(low)</th>
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<td>15</td>
<td>10</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>20</td>
<td></td>
<td>4.4</td>
</tr>
<tr>
<td>Upper Clay</td>
<td>2</td>
<td>14</td>
<td>10</td>
<td>20</td>
<td>4.4</td>
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<tr>
<td>Marine Clay</td>
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</tr>
<tr>
<td>Loose Sand</td>
<td>5</td>
<td>17</td>
<td>-</td>
<td></td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>Lower Clay</td>
<td>6.5</td>
<td>15</td>
<td>15</td>
<td>44</td>
<td>9.6</td>
</tr>
<tr>
<td>Marine Clay</td>
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<td></td>
<td></td>
<td>82</td>
<td>18</td>
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</table>

<table>
<thead>
<tr>
<th>Layer</th>
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<th>$S_u$(avg)</th>
<th>$S_u$(high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>$0 + 2.2h$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Upper Clay</td>
<td>$4.4 + 0.9h$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Lower Clay</td>
<td>$10 + 1.1h$</td>
<td>15</td>
<td>$10 + 1.1h$</td>
</tr>
</tbody>
</table>

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

Designated Shear Strength $= 10$ kPa

$S_u$(low) $= (0.22) \phi' \\
S_u$(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
Project B: Novena Station, Singapore
Observed and Predicted Wall Movements versus Depth

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

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<thead>
<tr>
<th>Parameter</th>
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<td>Total Unit Weight (kPa/m)</td>
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</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$(low)</td>
<td>0+3.1h</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>30</td>
</tr>
<tr>
<td><strong>Upper Marine Clay Layer (1.4-10m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>$\gamma$</td>
<td>15</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$(low)</td>
<td>4.4+1.1h</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>10+0.5h</td>
</tr>
<tr>
<td><strong>Sand Layer (10-13m)</strong></td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>$\gamma$</td>
<td>17</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$</td>
<td>10</td>
</tr>
<tr>
<td><strong>Lower Marine Clay Layer (13-20m)</strong></td>
<td></td>
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</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>$\gamma$</td>
<td>15</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$(low)</td>
<td>19+1.1h</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>19+1.1h</td>
</tr>
<tr>
<td><strong>Stiff Sandy Silt (20-55m)</strong></td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>$\gamma$</td>
<td>18.5</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$</td>
<td>70</td>
</tr>
<tr>
<td><strong>Wall Stiffness (kPa/m)</strong></td>
<td>EI</td>
<td>$4.56 \times 10^4$</td>
</tr>
<tr>
<td><strong>Strut Stiffness (kPa/m)</strong></td>
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<td></td>
</tr>
<tr>
<td>Strut 1 (at 1.5m)</td>
<td>AE/L</td>
<td>$1.82 \times 10^5$</td>
</tr>
<tr>
<td>Strut 2 (at 5m)</td>
<td>AE/L</td>
<td>$2.4 \times 10^5$</td>
</tr>
<tr>
<td>Strut 3 (at 7.5m)</td>
<td>AE/L</td>
<td>$3.88 \times 10^5$</td>
</tr>
<tr>
<td>Strut 4 (at 10.5m)</td>
<td>AE/L</td>
<td>$3.88 \times 10^5$</td>
</tr>
<tr>
<td>Strut 5 (at 13m)</td>
<td>AE/L</td>
<td>$3.88 \times 10^5$</td>
</tr>
<tr>
<td><strong>Excavation Width (m)</strong></td>
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<td>9</td>
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Table 6.9 (cont.)

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<td>Final Excavation Depth (m)</td>
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</tr>
<tr>
<td>Depth to Firm Layer (m)</td>
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</tr>
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<td>Surcharge Next to Excavation (kPa)</td>
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</tr>
<tr>
<td>Cantilever Movement Top of Wall (m)</td>
<td>CEM</td>
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</tr>
<tr>
<td>Cantilever Hinge Depth (m)</td>
<td>CEH</td>
<td>16</td>
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<tr>
<td>Unit Weight of Water (kPa/m)</td>
<td>$\gamma_w$</td>
<td>9.81</td>
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Table 6.10

Evaluation of Shear Strength Ranges for Case C

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth</th>
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<th>$S_u$</th>
<th>$\sigma'_v$</th>
<th>$S_u$(low)</th>
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</thead>
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<td>30</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td></td>
<td></td>
<td>20</td>
<td>4.4</td>
</tr>
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<td>Upper Marine Clay</td>
<td>1.4</td>
<td>15</td>
<td>10</td>
<td>20</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td>64.5</td>
<td>14.2</td>
</tr>
<tr>
<td>Loose Sand</td>
<td>10</td>
<td>17</td>
<td>-</td>
<td>64.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td></td>
<td></td>
<td>86.1</td>
<td></td>
</tr>
<tr>
<td>Lower Marine Clay</td>
<td>13</td>
<td>15</td>
<td>15</td>
<td>86.1</td>
<td>19</td>
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<td></td>
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<td>122.4</td>
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<th>$S_u$(avg)</th>
<th>$S_u$(high)</th>
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</thead>
<tbody>
<tr>
<td>Fill</td>
<td>0 + 3.1h</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Upper Clay</td>
<td>4.4 + 1.1h</td>
<td>10</td>
<td>10 + 0.5h</td>
</tr>
<tr>
<td>Lower Clay</td>
<td>19 + 1.1h</td>
<td>15</td>
<td>19 + 1.1h</td>
</tr>
</tbody>
</table>

Sand: $C_{eq} = "Equivalent Cohesion" = \sigma'_v K_0 \tan \phi$, and
\[ \phi = 30, K_0 = 0.9, \text{ so } C_{eq} = 40 \text{ kPa} \]
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 $\gamma_w = 9.81 \text{ kPa/m}$
Project C: Newton Cross-Over, Singapore

Observed and Predicted Movements versus Depth

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

<table>
<thead>
<tr>
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<td>Total Unit Weight (kPa/m)</td>
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<td>17</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$(low)</td>
<td>0+2.3h</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>30</td>
</tr>
<tr>
<td><strong>Upper Marine Clay Layer (3-13m)</strong></td>
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<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>τ</td>
<td>16</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$(low)</td>
<td>6.9+1.4h</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>15+0.6h</td>
</tr>
<tr>
<td><strong>Sand Layer (13-14m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Unit Weight (kPa/m)</td>
<td>τ</td>
<td>19</td>
</tr>
<tr>
<td>Undrained Shear Strength (kPa)</td>
<td>$S_u$(low)</td>
<td>20.5+2h</td>
</tr>
<tr>
<td></td>
<td>$S_u$(high)</td>
<td>30</td>
</tr>
<tr>
<td><strong>Wall Stiffness (kPa/m)</strong></td>
<td>EI</td>
<td>1.2 x 10⁶</td>
</tr>
<tr>
<td><strong>Strut Stiffness (kPa/m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strut 1 (at 0m)</td>
<td>AE/L</td>
<td>1.19 x 10⁶</td>
</tr>
<tr>
<td>Strut 2 (at 2m)</td>
<td>AE/L</td>
<td>1.19 x 10⁶</td>
</tr>
<tr>
<td>Strut 3 (at 7m)</td>
<td>AE/L</td>
<td>4.62 x 10⁵</td>
</tr>
<tr>
<td><strong>Excavation Width (m)</strong></td>
<td>B</td>
<td>21.2</td>
</tr>
<tr>
<td><strong>Excavation Length (m)</strong></td>
<td>L</td>
<td>100</td>
</tr>
<tr>
<td><strong>Final Excavation Depth (m)</strong></td>
<td>D</td>
<td>13.3</td>
</tr>
<tr>
<td><strong>Depth to Firm Layer (m)</strong></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td><strong>Surcharge Next to Excavation (kPa)</strong></td>
<td>q</td>
<td>0</td>
</tr>
<tr>
<td><strong>Cantilever Movement Top of Wall (m)</strong></td>
<td>CEM</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Cantilever Hinge Depth (m)</strong></td>
<td>CEH</td>
<td>16</td>
</tr>
<tr>
<td><strong>Unit Weight of Water (kPa/m)</strong></td>
<td>$\gamma_w$</td>
<td>9.81</td>
</tr>
</tbody>
</table>
### Table 6.12

**Evaluation of Shear Strength Ranges for Case D**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth</th>
<th>$\gamma$</th>
<th>$S_u$</th>
<th>$\sigma_v$</th>
<th>$S_u$(low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>0</td>
<td>17</td>
<td>30</td>
<td>-</td>
<td>0</td>
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<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>31.4</td>
<td>6.9</td>
</tr>
<tr>
<td>Upper Marine Clay</td>
<td>3</td>
<td>16</td>
<td>15</td>
<td>31.4</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td></td>
<td></td>
<td>93.3</td>
<td>20.5</td>
</tr>
<tr>
<td>Lower Clay</td>
<td>13</td>
<td>19</td>
<td>30</td>
<td>93.3</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td></td>
<td></td>
<td>102.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Lower Sand FIRM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Sand LAYER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer</th>
<th>$S_u$(low)</th>
<th>$S_u$(avg)</th>
<th>$S_u$(high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>$0 + 2.3h$</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Upper Clay</td>
<td>$6.9 + 1.4h$</td>
<td>15</td>
<td>15 + 0.6h</td>
</tr>
<tr>
<td>Lower Clay</td>
<td>$20.5 + 2h$</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

$S_u$(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
Project D: Newton Station Slurry Wall, Singapore

Observed and Predicted Wall Movements versus Depth

Figure 6.7 - MOEX Predictions for Case D

Excavation Depth in Feet

Movement in Inches
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.
Observed versus Predicted Lateral Wall Movements

Singapore and Chicago Case Histories

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.

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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.
References


Duncan, J. M., "Notes on Excavation Bracing," CE 5520 - Earth Pressures Class Notes, Virginia Polytechnic Institute and State University, Fall Quarter, 1985.
Goessling, S. E. H., "Interactive Design of Braced Excavations," thesis submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements of the degree of Master of Science in Civil Engineering, Blacksburg, Virginia, December, 1985.


Smith, M. L., "Braced Excavations: Three Case Histories in Chicago," project submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements of the degree of Master of Engineering in Civil Engineering, Blacksburg, Virginia, July, 1986.


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.

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

\[
d = \frac{2c}{\gamma}
\]

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):

\[ [L] = \text{length} \\
[F] = \text{force} \]

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:

\[ \text{MOPT} = 0 : \quad \text{vertical and lateral distribution of movement with respect to distance from wall calculated.} \]

\[ \text{MOPT} = 1 : \quad \text{movement distribution not calculated.} \]

NOPT = design option:

\[ \text{NOPT} = 0 : \quad \text{entire excavation geometry and stiffness is input; maximum lateral wall movement calculated for each excavation stage.} \]
\( \text{NOPT} = 1 \): excavation geometry and maximum allowable lateral wall movement input; wall stiffness \((EI)\) is calculated.

\( \text{NOPT} = 2 \): excavation geometry and stiffness, and maximum allowable lateral wall movement input; required strut spacing calculated.

\( \text{NOPT} = 3 \): excavation geometry and maximum allowable lateral wall movement input; required strut stiffness calculated.

D. CONTROL DATA

\( \text{NLAY}, \text{NSTRT}, \text{XKS} \), where:

\( \text{NLAY} \) — 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.

\( \text{NSTRT} \) — total number of struts in the excavation. Maximum of ten (10) struts (or tiebacks).

\( \text{XKS} \) — anisotropic strength ratio. Use \( \text{XKS} = 1.0 \) if soil is isotropic.

E. CANTILEVER EFFECT DATA

\( \text{CE}, \text{CEM}, \text{CEH} \), where:

\( \text{CE} \) = Cantilever Effect:

\( \text{CE} = 0 \) : no cantilever movements anticipated.

\( \text{CE} = 1 \) : cantilever movements are anticipated.

\( \text{CEM} \) = Cantilever movement at the top of the wall \([L]\).

\( \{\text{CEM} = 0 \text{ if } \text{CE} = 0\} \)
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, C0, 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$^3$].

C0 = 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:

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

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.

\[ S = \text{strut stiffness } [F/L \text{ per unit length of wall}], \text{ where: }\]
- \( A \) = 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:

$DLM = \text{maximum allowable lateral movement of the wall [L]}$.

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

**J, HS, S, where:**

$J = \text{strut number, starting with topmost strut as number 1.}$

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

$S = \text{strut stiffness [F/L per unit length of wall].}$

$- AE/L$ per unit length of wall, where:

$A = \text{cross-sectional area of the strut [L}^2\text{]}$

$E = \text{modulus of the strut material [F/L}^2\text{]}$

$L = \text{effective length of the strut [L]}$.

For $NOPT = 2$ (find average strut spacing)

**J. DISPLACEMENT DATA**

$DLM$, where:

$DLM = \text{maximum allowable lateral movement of the wall [L]}$.

**K. Wall Stiffness**

$EI$, where:

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

SAVG, where:

\[ SAVG = \frac{AE}{L} \text{ per unit length of wall} \]

where \( A \) = cross-sectional area of the struts \([L^2]\), \( E \) = average modulus of the strut materials \([F/L^2]\), and \( L \) = effective strut length \([L]\).

For NOPT = 3 (find strut stiffness)

J. DISPLACEMENT DATA

DLM, where:

\[ DLM = \text{maximum allowable lateral movement of the wall} \]

K. Wall Stiffness

EI, where:

\[ EI = \text{bending stiffness of the wall} \]

where \( E \) = modulus of the wall material \([F/L^2]\), and \( I \) = moment of inertia per unit length of wall \([L^4 \text{ per unit L}]\).

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

<table>
<thead>
<tr>
<th>OLD NOPT</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tbody>
<tr>
<td></td>
<td>---</td>
<td>DLM</td>
<td>DLM</td>
<td>DLM</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>SAVG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>EI</td>
<td>---</td>
<td>SAVG</td>
<td>EI</td>
</tr>
<tr>
<td>2</td>
<td>EI</td>
<td>J,HS,S</td>
<td>---</td>
<td>EI</td>
</tr>
<tr>
<td></td>
<td>J,HS,S</td>
<td></td>
<td>J,HS</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>J,HS,S</td>
<td>J,HS,S</td>
<td>SAVG</td>
<td>---</td>
</tr>
</tbody>
</table>
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-length² 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

<table>
<thead>
<tr>
<th>NOPT</th>
<th>INPUT</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>wall stiffness</td>
<td>FS at each stage</td>
</tr>
<tr>
<td></td>
<td>strut stiffness</td>
<td>maximum lateral movement</td>
</tr>
<tr>
<td></td>
<td>strut spacing</td>
<td>minimum FS</td>
</tr>
<tr>
<td>1</td>
<td>maximum allowable lateral wall movement</td>
<td>FS at each stage</td>
</tr>
<tr>
<td></td>
<td>strut spacing</td>
<td>required wall stiffness</td>
</tr>
<tr>
<td></td>
<td>strut stiffness</td>
<td>minimum FS</td>
</tr>
<tr>
<td>2</td>
<td>maximum allowable lateral wall movement</td>
<td>minimum FS</td>
</tr>
<tr>
<td></td>
<td>wall stiffness</td>
<td>required strut spacing</td>
</tr>
<tr>
<td></td>
<td>average strut stiffness</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>maximum allowable lateral wall movement</td>
<td>FS at each stage</td>
</tr>
<tr>
<td></td>
<td>wall stiffness</td>
<td>required average strut stiffness</td>
</tr>
<tr>
<td></td>
<td>strut spacing</td>
<td>minimum FS</td>
</tr>
</tbody>
</table>
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

\[ E = 4.2 \times 10^9 \text{ psf} \]

\[ I = 382 \text{ in}^4 \text{ per pile} \]

\[ = 220.6 \text{ in}^4 \text{ per foot wall} \]

\[ EI = 4.2 \times 10^9 \times 0.011 \text{ ft}^4/\text{ft wall} \]

\[ = 4.5 \times 10^7 \text{ lb} \cdot \text{ft}^2/\text{ft} \]

**steel struts** HP 12x74

\[ E = 4.2 \times 10^9 \text{ psf} \]

\[ A = 21.8 \text{ in}^2 = 0.15 \text{ ft}^2 \]

\[ L = 25 \text{ ft} \]

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

**wood strut**

\[ E = 2.5 \times 10^8 \]

\[ A = 1 \text{ ft}^2 \]

\[ L = 25 \text{ ft} \]

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

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

<table>
<thead>
<tr>
<th></th>
<th>English</th>
<th>Feet</th>
<th>PSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
<td>110.0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>91.0</td>
<td>350.00</td>
</tr>
<tr>
<td>3</td>
<td>70.0</td>
<td>96.0</td>
<td>450.00</td>
</tr>
<tr>
<td>100</td>
<td>62.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>500</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>45000000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>670000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1700000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1700000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**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**

<table>
<thead>
<tr>
<th>Number of soil layers</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of struts</td>
<td>3</td>
</tr>
<tr>
<td>Design Option</td>
<td>0</td>
</tr>
<tr>
<td>Anisotropic Strength Ratio</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**CANTILEVER EFFECT**

No Cantilever Movements are Anticipated

**SOIL LAYER DATA**

Layer number 1

<table>
<thead>
<tr>
<th>Thickness</th>
<th>10.00</th>
<th>Cohesion</th>
<th>.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>110.00</td>
<td>Coh. Increase</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 2

<table>
<thead>
<tr>
<th>Thickness</th>
<th>20.00</th>
<th>Cohesion</th>
<th>350.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>91.00</td>
<td>Coh. Increase</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 3

<table>
<thead>
<tr>
<th>Thickness</th>
<th>70.00</th>
<th>Cohesion</th>
<th>450.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>96.00</td>
<td>Coh. Increase</td>
<td>.00</td>
</tr>
</tbody>
</table>

Depth to firm layer from ground surface 100.000

**WATER TABLE DATA**

Unit weight of water 62.40

**EXCAVATION GEOMETRY**

<table>
<thead>
<tr>
<th>Total width of excavation</th>
<th>25.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length of excavation</td>
<td>500.00</td>
</tr>
<tr>
<td>Final depth of excavation</td>
<td>30.00</td>
</tr>
<tr>
<td>Surcharge next to excavation</td>
<td>.00</td>
</tr>
</tbody>
</table>
Wall Stiffness (EI) \[.450E+08\]

**STRUT DATA**

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.00</td>
<td>.6700E+06</td>
</tr>
<tr>
<td>2</td>
<td>14.00</td>
<td>.1700E+07</td>
</tr>
<tr>
<td>3</td>
<td>24.00</td>
<td>.1700E+07</td>
</tr>
</tbody>
</table>

**MOVEMENT CALCULATIONS**

Average Strut Spacing = 10.00
Nondimensional System Stiffness = 72.12

Excavation stage 2

Height of excavation is 14.00
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 24.00
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 30.00
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
—Comparison of Properties of Bay Mud from Custer Avenue and Rankin Street and Davidson Avenue

<table>
<thead>
<tr>
<th>Depth, in feet</th>
<th>Average Water Content, as a Percentage</th>
<th>Average Unit Weight, in Pounds per Cubic Foot (Kilograms per Cubic Meter)</th>
<th>Average Shear Strength, in Pounds per Square Foot (Pascals)</th>
<th>OCR</th>
<th>Sensitivity</th>
<th>PI, as a Percentage</th>
<th>LL, as a Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>(meters)</td>
<td>D³</td>
<td>C⁴</td>
<td>D⁵</td>
<td>C⁶</td>
<td>D⁷</td>
<td>C⁸</td>
<td>D⁹</td>
</tr>
<tr>
<td>0-30</td>
<td>95</td>
<td>92</td>
<td>91</td>
<td>92</td>
<td>350</td>
<td>500</td>
<td>1.4</td>
</tr>
<tr>
<td>(0-9)</td>
<td>(1,460)</td>
<td>(1,470)</td>
<td>(16,770)</td>
<td>(24,000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-55</td>
<td>75</td>
<td>65</td>
<td>96</td>
<td>104</td>
<td>450</td>
<td>800</td>
<td>1.0</td>
</tr>
<tr>
<td>(9-17)</td>
<td>(1,540)</td>
<td>(1,670)</td>
<td>(21,600)</td>
<td>(38,300)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*D = Davidson Avenue.  
*C = Custer Avenue and Rankin Street.  
*OCR = overconsolidation ratio.  
*Based on effective pressures with allowances for artesian pressure.

Note: 1 psf = 47.9 N/m²; 1 pcf = 0.157 kN/m³.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of soil layers</td>
<td>4</td>
</tr>
<tr>
<td>Number of struts</td>
<td>2</td>
</tr>
<tr>
<td>Design Option</td>
<td>0</td>
</tr>
<tr>
<td>Anisotropic Strength Ratio</td>
<td>1.000</td>
</tr>
</tbody>
</table>

CANTILEVER EFFECT

Expected Cantilever Movement at Top = 0.083
Anticipated Hinge Depth = 50.00

SOIL LAYER DATA

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Thickness</th>
<th>Unit Weight</th>
<th>Cohesion</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>125.00</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td>2</td>
<td>5.00</td>
<td>90.00</td>
<td>800.00</td>
<td>.00</td>
</tr>
<tr>
<td>3</td>
<td>49.00</td>
<td>120.00</td>
<td>900.00</td>
<td>.00</td>
</tr>
<tr>
<td>4</td>
<td>13.00</td>
<td>120.00</td>
<td>6000.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.00</td>
<td>.6480E+06</td>
</tr>
<tr>
<td>2</td>
<td>23.00</td>
<td>.8080E+06</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>.0965</td>
<td>.0347</td>
</tr>
<tr>
<td>4.50</td>
<td>.0965</td>
<td>.0695</td>
</tr>
<tr>
<td>9.00</td>
<td>.0917</td>
<td>.0888</td>
</tr>
<tr>
<td>13.50</td>
<td>.0724</td>
<td>.0946</td>
</tr>
<tr>
<td>18.00</td>
<td>.0579</td>
<td>.0907</td>
</tr>
<tr>
<td>22.50</td>
<td>.0434</td>
<td>.0791</td>
</tr>
<tr>
<td>27.00</td>
<td>.0289</td>
<td>.0627</td>
</tr>
<tr>
<td>31.50</td>
<td>.0241</td>
<td>.0482</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>.1652</td>
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<td>11.50</td>
<td>.1652</td>
<td>.1189</td>
</tr>
<tr>
<td>23.00</td>
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<td>.1520</td>
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<tr>
<td>34.50</td>
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<td>.1619</td>
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<tr>
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<td>.0991</td>
<td>.1553</td>
</tr>
<tr>
<td>57.50</td>
<td>.0743</td>
<td>.1355</td>
</tr>
<tr>
<td>69.00</td>
<td>.0496</td>
<td>.1074</td>
</tr>
<tr>
<td>80.50</td>
<td>.0413</td>
<td>.0826</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>15.00</td>
<td>.2445</td>
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<td>.2323</td>
<td>.1522</td>
</tr>
<tr>
<td>45.00</td>
<td>.1834</td>
<td>.1551</td>
</tr>
<tr>
<td>60.00</td>
<td>.1467</td>
<td>.1182</td>
</tr>
<tr>
<td>75.00</td>
<td>.1100</td>
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<td>.0642</td>
</tr>
<tr>
<td>105.00</td>
<td>.0611</td>
<td>.0453</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>.00</td>
<td>125.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 2

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>600.00</td>
<td>90.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 3

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.00</td>
<td>700.00</td>
<td>120.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 4

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.00</td>
<td>6000.00</td>
<td>120.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.00</td>
<td>.6480E+06</td>
</tr>
<tr>
<td>2</td>
<td>23.00</td>
<td>.8080E+06</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>.0965</td>
<td>.0347</td>
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<tr>
<td>4.50</td>
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<td>.0695</td>
</tr>
<tr>
<td>9.00</td>
<td>.0917</td>
<td>.0888</td>
</tr>
<tr>
<td>13.50</td>
<td>.0724</td>
<td>.0946</td>
</tr>
<tr>
<td>18.00</td>
<td>.0579</td>
<td>.0907</td>
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<tr>
<td>22.50</td>
<td>.0434</td>
<td>.0791</td>
</tr>
<tr>
<td>27.00</td>
<td>.0289</td>
<td>.0627</td>
</tr>
<tr>
<td>31.50</td>
<td>.0241</td>
<td>.0482</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>.2364</td>
<td>.0383</td>
</tr>
<tr>
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<tr>
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<tr>
<td>80.50</td>
<td>.0591</td>
<td>.0290</td>
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</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>.0731</td>
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<tr>
<td>105.00</td>
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<td>.0346</td>
</tr>
</tbody>
</table>
## 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**

<table>
<thead>
<tr>
<th>Number of soil layers</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of struts</td>
<td>3</td>
</tr>
<tr>
<td>Design Option</td>
<td>0</td>
</tr>
<tr>
<td>Anisotropic Strength Ratio</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**CANTILEVER EFFECT**

Expected Cantilever Movement at Top = 0.330
Anticipated Hinge Depth = 45.00

**SOIL LAYER DATA**

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.00</td>
<td>0.00</td>
<td>120.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>38.50</td>
<td>800.00</td>
<td>110.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>32.50</td>
<td>2000.00</td>
<td>110.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Depth to firm layer from ground surface 48.500

**WATER TABLE DATA**

Unit weight of water 62.40
EXCAVATION GEOMETRY

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total width of excavation</td>
<td>120.00</td>
</tr>
<tr>
<td>Total length of excavation</td>
<td>210.00</td>
</tr>
<tr>
<td>Final depth of excavation</td>
<td>32.50</td>
</tr>
<tr>
<td>Surcharge next to excavation</td>
<td>100.00</td>
</tr>
<tr>
<td>Wall Stiffness (EI)</td>
<td>.136E+08</td>
</tr>
</tbody>
</table>

STRUT DATA

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.00</td>
<td>.1410E+07</td>
</tr>
<tr>
<td>2</td>
<td>14.00</td>
<td>.2090E+07</td>
</tr>
<tr>
<td>3</td>
<td>25.00</td>
<td>.2090E+07</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>.3200</td>
<td>.2304</td>
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<tr>
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<tr>
<td>6.00</td>
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<td>.3008</td>
</tr>
<tr>
<td>7.50</td>
<td>.1440</td>
<td>.2624</td>
</tr>
<tr>
<td>9.00</td>
<td>.0960</td>
<td>.2080</td>
</tr>
<tr>
<td>10.50</td>
<td>.0800</td>
<td>.1600</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
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<tr>
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<td>.2400</td>
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</tr>
<tr>
<td>28.00</td>
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<td>.3008</td>
</tr>
<tr>
<td>35.00</td>
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<td>.2624</td>
</tr>
<tr>
<td>42.00</td>
<td>.0960</td>
<td>.2080</td>
</tr>
<tr>
<td>49.00</td>
<td>.0800</td>
<td>.1600</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<tr>
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<td>.0501</td>
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</tbody>
</table>

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

<table>
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<td>.0440</td>
</tr>
</tbody>
</table>
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 = 0.330
- Anticipated Hinge Depth = 45.00

SOIL LAYER DATA

Layer number 1
- Thickness: 10.00
- Cohesion: 0.00
- Unit Weight: 120.00
- Coh. Increase: 0.00

Layer number 2
- Thickness: 38.50
- Cohesion: 600.00
- Unit Weight: 110.00
- Coh. Increase: 0.00

Layer number 3
- Thickness: 32.50
- Cohesion: 1500.00
- Unit Weight: 110.00
- Coh. Increase: 0.00

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

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>14.00</td>
<td>.2090E+07</td>
</tr>
<tr>
<td>3</td>
<td>25.00</td>
<td>.2090E+07</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>.3200</td>
<td>.1152</td>
</tr>
<tr>
<td>1.50</td>
<td>.3200</td>
<td>.2304</td>
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<tr>
<td>3.00</td>
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<tr>
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<td>.2624</td>
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<tr>
<td>9.00</td>
<td>.0960</td>
<td>.2080</td>
</tr>
<tr>
<td>10.50</td>
<td>.0800</td>
<td>.1600</td>
</tr>
</tbody>
</table>
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

<table>
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<td>28.00</td>
<td>.2039</td>
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<td>35.00</td>
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<tr>
<td>49.00</td>
<td>.0850</td>
<td>.0640</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
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<tr>
<td>87.50</td>
<td>.1251</td>
<td>.0537</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>.6191</td>
<td>.3009</td>
</tr>
<tr>
<td>65.00</td>
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<td>.2009</td>
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<td>81.25</td>
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<td>.1243</td>
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<tr>
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<td>.1549</td>
<td>.0739</td>
</tr>
<tr>
<td>113.75</td>
<td>.1338</td>
<td>.0342</td>
</tr>
</tbody>
</table>
**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**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of soil layers</td>
<td>4</td>
</tr>
<tr>
<td>Number of struts</td>
<td>3</td>
</tr>
<tr>
<td>Design Option</td>
<td>0</td>
</tr>
<tr>
<td>Anisotropic Strength Ratio</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**CANTILEVER EFFECT**

Expected Cantilever Movement at Top = .083

Anticipated Hinge Depth = 30.00

**SOIL LAYER DATA**

Layer number 1

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
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<td>.00</td>
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</tbody>
</table>

Layer number 2

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<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
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<td>.00</td>
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</tbody>
</table>

Layer number 3

<table>
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<tr>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
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<td>125.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 4

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<th>Unit Weight</th>
<th>Coh. Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.00</td>
<td>2000.00</td>
<td>125.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

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) 0.380E+08

STRUT DATA

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
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<tbody>
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<tr>
<td>2</td>
<td>12.00</td>
<td>0.1110E+07</td>
</tr>
<tr>
<td>3</td>
<td>24.00</td>
<td>0.1590E+07</td>
</tr>
</tbody>
</table>

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 0.026
Cantilever Movement at this Stage is 0.072
Total Wall Movement at this Stage is 0.098
Overall Maximum Lateral Wall Movement is 0.098
Est. Distribution of Ground Surface Movement

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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

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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

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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

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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

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<td>Anisotropic Strength Ratio</td>
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CANTILEVER EFFECT

Expected Cantilever Movement at Top = 0.083
Anticipated Hinge Depth = 30.00

SOIL LAYER DATA

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<th>Coh. Increase</th>
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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

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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 0.038
Cantilever Movement at this Stage is 0.072
Total Wall Movement at this Stage is 0.110
Overall Maximum Lateral Wall Movement is 0.110

Est. Distribution of Ground Surface Movement

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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

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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

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**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

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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

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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

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**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 = 0.75

Lateral Wall Movement at this Stage is 0.010
Cantilever Movement at this Stage is 0.008
Total Wall Movement at this Stage is 0.018
Overall Maximum Lateral Wall Movement is 0.018

### Est. Distribution of Ground Surface Movement

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**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 = 0.75

Lateral Wall Movement at this Stage is 0.023
Cantilever Movement at this Stage is 0.007
Total Wall Movement at this Stage is 0.030
Overall Maximum Lateral Wall Movement is 0.030

Est. Distribution of Ground Surface Movement

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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 = 0.75

Lateral Wall Movement at this Stage is 0.047
Cantilever Movement at this Stage is 0.007
Total Wall Movement at this Stage is 0.054
Overall Maximum Lateral Wall Movement is 0.054

Est. Distribution of Ground Surface Movement

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</tr>
</tbody>
</table>

Average Strut Stiffness = 147000.00

| Alpha D = | 1.00 |
| Alpha B = | 1.62 |
| Alpha S = | 0.75 |

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

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Excavation stage 6

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Average Strut Stiffness = 149000.00

| Alpha D = | 1.00 |
| Alpha B = | 1.49 |
| Alpha S = | 0.75 |

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

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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 = 0.74

Lateral Wall Movement at this Stage is 0.099
Cantilever Movement at this Stage is 0.004
Total Wall Movement at this Stage is 0.104
Overall Maximum Lateral Wall Movement is 0.104

Est. Distribution of Ground Surface Movement

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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 0.00

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 0.00
Wall Stiffness (EI) 1.140E+05

STRUT DATA

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<tr>
<td>6</td>
<td>9.75</td>
<td>1.1590E+06</td>
</tr>
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</table>

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 = 0.75

Lateral Wall Movement at this Stage is 0.003
Cantilever Movement at this Stage is 0.009
Total Wall Movement at this Stage is 0.012
Overall Maximum Lateral Wall Movement is 0.012
Est. Distribution of Ground Surface Movement

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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

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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 = 0.75

Lateral Wall Movement at this Stage is 0.037
Cantilever Movement at this Stage is 0.007
Total Wall Movement at this Stage is 0.045
Overall Maximum Lateral Wall Movement is 0.045

Est. Distribution of Ground Surface Movement

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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 = 0.75

Lateral Wall Movement at this Stage is 0.076
Cantilever Movement at this Stage is 0.007
Total Wall Movement at this Stage is 0.082
Overall Maximum Lateral Wall Movement is 0.082

Est. Distribution of Ground Surface Movement

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</table>
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

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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

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</table>

**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

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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

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<th>Depth</th>
<th>Stiffness</th>
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</table>

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

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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

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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

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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

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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

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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

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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

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**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**

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<th>Number of soil layers</th>
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<td>Anisotropic Strength Ratio</td>
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**CANTILEVER EFFECT**

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

**SOIL LAYER DATA**

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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

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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

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**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 = 0.75

Lateral Wall Movement at this Stage is 0.027
Cantilever Movement at this Stage is 0.090
Total Wall Movement at this Stage is 0.117
Overall Maximum Lateral Wall Movement is 0.117

### Est. Distribution of Ground Surface Movement

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**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

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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

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</table>

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

<table>
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<tr>
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<tbody>
<tr>
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</tr>
</tbody>
</table>

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

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</table>
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

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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 = 0.068
Anticipated Hinge Depth = 5.00

SOIL LAYER DATA

Layer number 1
Thickness 1.40 Cohesion 30.00
Unit Weight 17.00 Coh. Increase 0.00

Layer number 2
Thickness 8.60 Cohesion 10.00
Unit Weight 15.00 Coh. Increase 0.50

Layer number 3
Thickness 3.00 Cohesion 10.00
Unit Weight 17.00 Coh. Increase 0.00

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 0.00
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: 0.00
Wall Stiffness (EI): 4.56E+05

**STRUT DATA**

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</table>

**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 = 0.75

Lateral Wall Movement at this Stage is: 0.005
Cantilever Movement at this Stage is: 0.048
Total Wall Movement at this Stage is: 0.052
Overall Maximum Lateral Wall Movement is: 0.052
Est. Distribution of Ground Surface Movement

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</table>

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

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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

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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

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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

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</table>
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

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### 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

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<td>Anisotropic Strength Ratio</td>
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#### CANTILEVER EFFECT

No Cantilever Movements are Anticipated

#### SOIL LAYER DATA

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</table>
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

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<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
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<tr>
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<td>13.00</td>
<td>.3880E+06</td>
</tr>
</tbody>
</table>

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

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</table>

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

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</table>
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

<table>
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</table>

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 \(0.180\)
Overall Maximum Lateral Wall Movement is \(0.180\)

Est. Distribution of Ground Surface Movement

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Excavation stage 5

Height of excavation is \(13.000\)
Factor of safety against basal heave is \(0.6454\)
Minimum factor of safety between stages is \(0.5990\)

**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 = \(0.98\)
Alpha S = \(0.75\)

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 \(0.215\)
Overall Maximum Lateral Wall Movement is \(0.215\)
Est. Distribution of Ground Surface Movement

<table>
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<td>.0215</td>
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<td>.0129</td>
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<tr>
<td>45.50</td>
<td>.0194</td>
<td>.0043</td>
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</table>

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

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<tr>
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<tr>
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</table>
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

<table>
<thead>
<tr>
<th>Number of soil layers</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of struts</td>
<td>3</td>
</tr>
<tr>
<td>Design Option</td>
<td>0</td>
</tr>
<tr>
<td>Anisotropic Strength Ratio</td>
<td>1.000</td>
</tr>
</tbody>
</table>

CANTILEVER EFFECT

Expected Cantilever Movement at Top = .060
Anticipated Hinge Depth = 16.00

SOIL LAYER DATA

Layer number 1

<table>
<thead>
<tr>
<th>Thickness</th>
<th>3.00</th>
<th>Cohesion</th>
<th>30.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
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<td>Coh. Increase</td>
<td>.00</td>
</tr>
</tbody>
</table>

Layer number 2

<table>
<thead>
<tr>
<th>Thickness</th>
<th>10.00</th>
<th>Cohesion</th>
<th>15.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>16.00</td>
<td>Coh. Increase</td>
<td>.60</td>
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</tbody>
</table>

Layer number 3

<table>
<thead>
<tr>
<th>Thickness</th>
<th>1.00</th>
<th>Cohesion</th>
<th>30.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight</td>
<td>19.00</td>
<td>Coh. Increase</td>
<td>.00</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.00</td>
<td>.1189E+07</td>
</tr>
<tr>
<td>2</td>
<td>2.00</td>
<td>.1189E+07</td>
</tr>
<tr>
<td>3</td>
<td>7.00</td>
<td>.4623E+06</td>
</tr>
</tbody>
</table>

MOVENT 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

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>.00</td>
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<td>7.00</td>
<td>.0249</td>
<td>.0498</td>
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</table>
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

<table>
<thead>
<tr>
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<tr>
<td>24.50</td>
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</table>

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

<table>
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<tr>
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<td>.0060</td>
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<tr>
<td>46.55</td>
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</table>
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

<table>
<thead>
<tr>
<th>Number of soil layers</th>
<th>3</th>
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<tbody>
<tr>
<td>Number of struts</td>
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</tr>
<tr>
<td>Design Option</td>
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</tr>
<tr>
<td>Anisotropic Strength Ratio</td>
<td>1.000</td>
</tr>
</tbody>
</table>

CANTILEVER EFFECT

Expected Cantilever Movement at Top = 0.060
Anticipated Hinge Depth = 16.00

SOIL LAYER DATA

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Thickness</th>
<th>Cohesion</th>
<th>Unit Weight</th>
<th>Coh. Increase</th>
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<tbody>
<tr>
<td>1</td>
<td>3.00</td>
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<td>17.00</td>
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</tr>
<tr>
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<td>Cohesion</td>
<td>Unit Weight</td>
<td>Coh. Increase</td>
</tr>
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<td>10.00</td>
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</tr>
<tr>
<td>Layer number 3</td>
<td>Thickness</td>
<td>Cohesion</td>
<td>Unit Weight</td>
<td>Coh. Increase</td>
</tr>
<tr>
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<td>1.00</td>
<td>20.50</td>
<td>19.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

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 0.00
Wall Stiffness (EI) 1.20E+07

STRUT DATA

<table>
<thead>
<tr>
<th>Strut</th>
<th>Depth</th>
<th>Stiffness</th>
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</thead>
<tbody>
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<tr>
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<tr>
<td>3</td>
<td>7.00</td>
<td>4.623E+06</td>
</tr>
</tbody>
</table>

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 = 0.75

Lateral Wall Movement at this Stage is 0.007
Cantilever Movement at this Stage is 0.052
Total Wall Movement at this Stage is 0.060
Overall Maximum Lateral Wall Movement is 0.100

Est. Distribution of Ground Surface Movement

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</table>
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

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<tr>
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<td>.0125</td>
<td>.0028</td>
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</table>

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

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<td>33.25</td>
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<td>.0139</td>
<td>.0083</td>
</tr>
<tr>
<td>46.55</td>
<td>.0125</td>
<td>.0028</td>
</tr>
</tbody>
</table>
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
C of 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),
  fs(20),disp(20),d(8,20),s(20),disp(20),d(8,20),sv(8,20),
  l(20),j(20),hs(20),
  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/,
  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: '//' , 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(1H0,' ',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(1H0,T5,'The units of length are - ',' ',A15,/ 1 1H0,T5,'The units of stress are - ',' ',A15)
READ(5,*) mopt,nopt
READ(5,*) nlay,nstrt,xks
WRITE(io,260)nlay,nstrt,mopt,xks
WRITE(io,260) nlay,nstrt,mopt,xks
260 FORMAT(1H0,T5,'CONTROL DATA'/
1 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'/
1 1H+,T5,'_________________')
264 FORMAT(1H0,T10,'No Cantilever Movements are
Aanted')
265 FORMAT(1H0,T10,'Expected Cantilever Movement at Top
=','T51,F6.3/
1 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
d=0
DO 280 i=1,nlay
   WRITE(io,300) i
   WRITE(io,310) h(i),c0(i)
   WRITE(io,320) gt(i),dc(i)
d=d+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'/
       1H+,T5,''_/_/
       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
..............nopt=0 input..............
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'/
1 1H+, T5, '____________', /
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)

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

............. nopt=1 input .............
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

............. nopt=2 input .............
470 READ (5,*) dlm
WRITE (io, 460) dlm
480 FORMAT (T10, 'Average strut stiffness', 6X, E13.4)
WRITE (io, 490)
490 FORMAT (1H0, T5, 'STRUT SPACING CALCULATIONS'/
1 1H+, T5, '_______________________')
DO 500 i=1,5
    hs(i)=hw/5
500 CONTINUE
GOTO 563

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'/
1 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
..............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) --> '/'
2 20X,'\')
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
...............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.....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(IHO,T15,'Average Strut Spacing =',T59,F7.2)
C
C.....compute system stiffness
C
systf=A LOG10(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

ENDF
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,fseelm,ak)
      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,fseelm,CE,CEM,CEH,systf)
      IF(mopt.EQ.0) CALL DSTRB(m,fs,he,disp,d,dv,dl,fseelm)
      600 CONTINUE
      c
      IF(nopt.EQ.0) GOTO 630
      IF(nopt.EQ.1) THEN
      CALL SDISP(fs,disp,dlm,gm,he,ei,havg,savg,df,ms,
      1 nopt,gw,fseelm,CE,CEM,CEH,systf)
      IF(mopt.EQ.0) THEN
      disp(ms)=dlm
      CALL DSTRB(ms,fs,he,disp,d,dv,dl,fseelm)
      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)
      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,he,ei,havg,savg,df,ms,nopt,
      1 gw,fseelm,CE,CEM,CEH,systf)
      IF(mopt.EQ.0) THEN
      disp(ms)=dlm
CALL DSTRB(ms, fs, hw, disp, d, dv, dl, fselmn)
ENDIF
ENDIF

630  CLOSE (5)
ENDIF
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

660  STOP
END
SUBROUTINE FSHEAV (hs, m, k, gw, nlay, h, c0, dc, gt, fs, gm, 
    he, df, nopt, fselmn, ak)

DIMENSION hs(20), h(20), c0(20), dc(20), gt(20), fs(20), 
    fsel(20), fsmd(20), fselmn(20), hsum(20), 
    t(20), botlay(20), fsdf(20), dcr(20)

COMMON de, hw, b, q, i¤, eln

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

DO 200 i=1,10
    hei=hei+(0.1* hs(m))

fsmd(i)=100.0
hsum(0)=0
t(0)=0
pe=0
rc=0
hsid=0
htob=0
Tfail=0
HT=0
tsum=0
subt=0
subb=0
sub=0
bresis=0
fsel(i)=100.0
qm=0
dfirm=df
botlay(0)=0
ndf=0
dcrit(i)=df
c..evaluates soil layers of influence on given excav. depth
c.
DO 100 j=1,nlay
c.......add next soil layer........
c
   hsum(j)=hsum(j-1)+h(j)
c
..compute effects of soil layer j if above excav. bottom
IF (hsum(j).LE.hei)THEN
  
c..rc = resistance to sliding (from cohesion) on vertical
failure plane.....
   rc = rc+(c0(j)+dc(j)*h(j)/2)*h(j)
  
c..pe = total stress sum (bearing stress due to soil weight
of layers adjacent to excavation.
   pe = pe+gt(j)*h(j)
  
c.......loops back if excav. bottom has not been reached
IF (hsum(j).LT.hei) THEN
   t(j)=0
   GOTO 100
ENDIF
ENDIF
  
c..adds effects of portions of layers above excav. bottom
......where hside = layer thickness above excav. bottom
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..evaluate the bottom of all soil layers for critical
depth to failure surface (the failure surface which gives
the lowest factor of safety for that excavation depth)
......botlay(n) = depth to bottom of soil layer n
......ndf = number of soil layers below excav. bottom
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......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 compute bearing resistance of layers below excav. bottom
c.subt = undrained shear strength of layer \( j \) at top of layer
c.where "top" is defined as at or below excav. bottom
c.subb=undrained shear strength of layer \( j \) at bottom of layer
c.where "bottom" is defined as at or above failure surface
c

\[
\text{IF} \ (hsum(j-1) \ < \ hei) \ \text{THEN} \\
\text{subt} = c0(j) + dc(j)*(hei-hsum(j-1)) \\
\text{subb} = \text{subt} + dc(j)*t(j) \\
\text{ELSE} \\
\text{subt} = c0(j) \\
\text{subb} = c0(j) + dc(j)*t(j) \\
\text{ENDIF}
\]

c.sub = average of subt and subb (used for layers
increasing in shear strength with depth)
c.bresis = bearing resistance sum provided by soil layers
below excav. bottom and above failure surface

c sub = (subt + subb)/2
bresis = bresis + sub*t(j)
c

.....loops back to consider all soil layers to failure
......surface before calculating factor of safety
c
t(j)=t(j)+t(j-1)
\text{IF} \ (hsum(j) < HT) \ \text{GOTO 100}
c

.....Bearing capacity factor
50
bcf=5*(1.0+0.2*(b/eln))
c

.....factor of safety

\[
\text{IF} \ (((pe+q)*Tfail) \leq rc) \ \text{THEN} \\
\text{IF} \ (j \ = \ 1) \ \text{fsmd}(j) = \text{fs}(m-1) \\
\text{IF} \ (j > 1) \ \text{fsmd}(j) = \text{fsmd}(j-1) \\
\text{GOTO 100} \\
\text{ENDIF}
\]

c

c.computes new factor of safety for each firm layer...
.........(ak = anisotropic strength ratio)
261

\[ \text{fsdf}(n) = (bcf \times bresis \times ak) / ((pe+q) \times T\text{fail} - rc) \]

......computes minimum factor of safety between the different firm layers

\[ \text{IF (fsmd}(j) \text{.GT. fsdf}(n)) \text{ THEN} \]
\[ \text{fsmd}(j) = \text{fsdf}(n) \]
\[ \text{dcrit}(j) = \text{dfirm} \]
\[ \text{ENDIF} \]

80 CONTINUE

......computes minimum factor of safety...........

\[ \text{IF (fsel}(i) \text{.GT. fsmd}(j)) \text{ THEN} \]
\[ \text{fsel}(i) = \text{fsmd}(j) \]
\[ \text{dcrit}(i) = \text{dcrit}(j) \]
\[ \text{ENDIF} \]

stops iterating if depth has reached failure surface or

firm layer....

\[ \text{IF (hsum}(j) \text{.GE. HT) GOTO 101} \]

100 CONTINUE

101 \[ \text{IF (fsel}(i) \text{.LT. fselmn}(m)) \text{ THEN} \]
\[ \text{fselmn}(m) = \text{fsel}(i) \]
\[ \text{dcrit}(m) = \text{dcrit}(i) \]
\[ \text{ENDIF} \]
\[ \text{IF (fselmn}(m) \text{.GT. fselmn}(m-1)) \text{ fselmn}(m) = \text{fselmn}(m-1) \]

fs(m) = fsel(10)

200 CONTINUE

he = hei

\[ \text{IF (nopt.EQ.2) GOTO 615} \]

210 \text{WRITE (io,211)hei}

211 \text{FORMAT (T15,'Depth of excavation is ',',F10.3)}

\text{WRITE (io,216) fs(m)}

\text{WRITE (io,217) fselmn(m)}

\text{WRITE (io,218) dcrit(m)}

216 \text{FORMAT (T15,'Factor of safety against basal heave is ',',F8.4)}

217 \text{FORMAT (T15,'Minimum factor of safety between stages is ',',F8.4)}

218 \text{FORMAT (T15,'Bottom of failure surface at minimum FS is ',',F8.4)}
IF (fseilmn(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
SUBROUTINE SDISP - FINDS DISPLACEMENT

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),
4 fsx14a(11), fsy14a(11), fsx20a(11), fsy20a(11),
5 fsx30a(11), fsy30a(11), adx(4), ady(4), abx(4),
6 aby(4), asx(4), asy(4), asxa(4), asya(4), fs(20),
7 s(20), disp(20), fsx(11), fsy(11), asxl(4),
8 fselmn(20), fsxa(11), fsysa(11),
9 fxb(11), fsyb(11), fsx9a(11), fsy9a(11)

COMMON de, hw, b, q, io, eln

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, 2.5, 2.0, 1.625, 1.5, 1.45, 1.3, 1.22,
1 1.15, 1.1, 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/, fsx11/3.0,
2 .5, 2.0, 1.75, 1.55, 1.3, 1.2, 1.1, 1.0,
3 0.92, 0.825/, fsx14/20.0, 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, 1.25, 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, 1.3, 1.45, 1.5, 1.625,
1 2.0, 2.5, 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/,
7 fsy11a/3000.0, 700.0, 300.0, 200.0, 150.0, 100.0,
8 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, 0.8/, 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/
5  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/,
10   asy/1.17,1.0,0.785,0.75/,
11   asxa/1666.7,533.3,133.3,60.0/,
12   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
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)
40 CONTINUE
WRITE(io, 45) as
45 FORMAT(T15,'Alpha S = ', T52, F14.2)
IF (nopt .EQ. 0) GOTO 50
IF (nopt .EQ. 1) GOTO 140
IF (nopt .EQ. 2) GOTO 140
C...........NOPT = 0 (find maximum displacement)............
50 n = 11
C.WRITES WARNING MESSAGE IF STIFFNESS EXCEEDS DATA CURVES
C
IF (systf .GE. 3.5) THEN
   WRITE (io, 310)
   systf = 3.5
ENDIF
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)
      systf = 1.0
   ENDIF
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.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.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.CALCULATES 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

CALCULATES LINEAR INTERPOLATION BETWEEN 1.1>FS>=1.0 CURVES.

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)
  CONTINUE
  DO 101 i=1,11
    fsxb(i)=fsx11(i)
    fsyb(i)=fsy11(i)
  CONTINUE
  FSA=1.0
  FSB=1.1
ENDIF

CALCULATES LINEAR INTERPOLATION BETWEEN 1.0>FS>=0.9 CURVES.

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)
  CONTINUE
  DO 103 i=1,11
    fsxb(i)=fsx10(i)
    fsyb(i)=fsy10(i)
  CONTINUE
  FSA=0.9
  FSB=1.0
ENDIF

C.COMPUTES MOVEMENTS FOR FS<0.9 USING FS=0.9 CURVES

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)
  CONTINUE
  DO 107 i=1,11
    fsx(i)=ALOG10(fsx(i))
  CONTINUE
CALL COEFS(n,fsx,fsy,systf,dh)
ENDIF
GOTO 120
DO 110 i=1,11
   fsxa(i)=ALOG10(fsxa(i))
   fsxb(i)=ALOG10(fsxb(i))
110 CONTINUE
C.............COMPUTE AVERAGE FROM GIVEN CURVES.............
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...(to be used for debugging)
* WRITE(io,*)'dh=',dh,' dha=',dha,' dhb=',dhb
C
120 IF(nopt.EQ.3) GOTO 260
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.................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......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........nopt=1 and nopt=2 curves......
140 n=11
    dh=dml/(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
    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
ENDDIF

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
ENDDIF

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)
  CONTINUE
  DO 194 i=1,11
    fsxb(i)=fsx10a(i)
    fsyb(i)=fsy10a(i)
  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)
  CONTINUE
  DO 198 i=1,11
    fsy(i)=ALOG10(fsy(i))
  CONTINUE
  CALL COEFS(n,fsx,fsy,dh,systf)
  GOTO 205
ENDIF

DO 200 i=1,11
  fsya(i)=ALOG10(fsy(i))
  fsyb(i)=ALOG10(fsyb(i))
CONTINUE

CALL COEFS(n,fsxa,fsya,dh,systfa)
CALL COEFS(n,fsxb,fsyb,dh,systfb)

C
c......COMPUTES SYSTEM STIFFNESS REQUIRED
c sstf=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 e=(10.0**sstf)*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**sstf)*gw))**0.25
WRITE(io,250) havg
250 FORMAT(1H0,T10,'Required average strut spacing=',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 VERIFY INPUT'/
   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. PLEASE VERIFY INPUT'/
   2 1H,T20,'VALUES OF STRUT STIFFNESS & SPACING AND WALL'/
   3 1H,T20,'STIFFNESS FOR ACCURACY.')
330 FORMAT(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
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

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)
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

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)+he
i=i+1
IF(i.EQ.9) GOTO 150
GOTO 140

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))

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)+he
i=i+1
IF(i.EQ.9) GOTO 150
GOTO 140

150

CONTINUE

C
C ........distrib. of lateral movement...(fig. 3.10)....
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/

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 COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN
        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 COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN
        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 COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN
        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 COMPUTES MOVEMENTS BASED ON LINEAR INTERPOLATION BETWEEN CURVES WHERE FS>2.2

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

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)

RETURN
END
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
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
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
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)

    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)

    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)

    330 WRITE(*,340) J(I),DC(I)
340 FORMAT(//20X,' Cohesion increase of layer ',I2,/)
      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(/' New cohesion increase --> '
READ(*,*) DC(I)
390 CONTINUE
C
400 WRITE(*,410)
410 FORMAT(/' 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(/' New depth to firm layer --> '
READ(*,*) df
440 WRITE(*,450)
450 FORMAT(/' 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(/' New unit weight of water --> '
READ(*,*) gw
480 WRITE(*,490)
490 FORMAT(/' 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(/' New excavation width --> '
READ(*,*) b
WRITE(*,520)
520 FORMAT(/' New excavation length --> '
READ(*,*) eln
WRITE(*,530)
530 FORMAT(/' New final excavation depth --> '
READ(*,*) hw
WRITE(*,540)
540 FORMAT(/' 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/
   20x,'Change wall stiffness? (yes=1, no=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 ='
   20x,'Change average strut stiffness? (yes=1, no=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/
   20x,'Change number of struts? (yes=1, no=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)'/
**Translation of the Code:**

```plaintext
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

IF(nopt.EQ.3) GOTO 770

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(*,*) $(1)
760 CONTINUE

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

IF(nopt.EQ.0) GOTO 790
IF(nopt.EQ.1) GOTO 820
IF(nopt.EQ.2) GOTO 830
```

**Translation Notes:**

- The code snippet appears to be a part of a larger program dealing with structural analysis, possibly related to finite element analysis.
- The code includes various loops and conditional statements for handling different scenarios.
- The variables `iyn`, `i`, `hs(i)`, `hstrt`, `ms`, `hw`, `nopt`, etc., are used within the context of the program.
- The format statements (`FORMAT`) are used to print formatted output to the screen or to a file.
- The conditional statements (`IF`) are used to control the flow of the program based on user input or certain conditions.
- The program includes loops (`DO`) that iterate over different elements or values.
- The program seems to be designed to handle multiple inputs and outputs, including data input and output to files or the console.

**Purpose:**

The code likely aims to calculate and display new spacings or stiffnesses for struts based on user input, and to write data into a file.
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
SUBROUTINE COEFS

SUBROUTINE COEFS(n,x,y,a,b)
DIMENSION x(n), y(n), c(4,4), d(4), work(4), ipvt(4)

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
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
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

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
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

CONTINUE
DO 30 j = k + 1, 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 = k + 1, n
    a(i, j) = a(i, j) + a(i, k) * t
  CONTINUE
30 CONTINUE
35 CONTINUE

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)
  CONTINUE
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

DO 60 kb = 1, n - 1
  k = n - kb
  t = 0.0
  kp1 = k + 1
  DO 55 i = kp1, n
    t = t + a(i, k) * work(k)
  CONTINUE
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

ynorm = 0.0
DO 65 i = 1, n
  ynorm = ynorm + abs(work(i))
65 CONTINUE

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
RETURN
END

SUBROUTINE SOLVE
SUBROUTINE SOLVE(ndim,n,a,b,ipvt)
INTEGER ndim,n,ipvt(n)
REAL a(ndim,n),b(n)
IF(n.EQ.1) GOTO 50
nl=m-1
DO 20 k=1,nl
   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

DO 40 kb=1,nl
   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)
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
ein = excavation length
fdb = depth of failure mechanism
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 htab
ht = incremental layer thickness sum
htab = 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
ss = 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
sysn = nondimensionalized strut stiffness
t(j) = thickness of layer j, portion of layer below excavation bottom only
Tfail = distance from 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'
axx = --coordinates of ak in Figure 4.4
aky =
\[
\begin{align*}
\text{fsx10} & \quad \text{coordinates of FS = 1.0 curve in Figure 2.7} \\
\text{fsy10} & \\
\text{fsx11} & \quad \text{coordinates of FS = 1.1 curve in Figure 2.7} \\
\text{fsy11} & \\
\text{fsx14} & \quad \text{coordinates of FS = 1.4 curve in Figure 2.7} \\
\text{fsy14} & \\
\text{fsx20} & \quad \text{coordinates of FS = 2.0 curve in Figure 2.7} \\
\text{fsy20} & \\
\text{fsx30} & \quad \text{coordinates of FS = 3.0 curve in Figure 2.7} \\
\text{fsy30} & \\
\text{fsx10a} & \quad \text{inverted coordinates of FS = 1.0 curve, Fig 2.7} \\
\text{fsy10a} & \\
\text{fsx11a} & \quad \text{inverted coordinates of FS = 1.1 curve, Fig 2.7} \\
\text{fsy11a} & \\
\text{fsx14a} & \quad \text{inverted coordinates of FS = 1.4 curve, Fig 2.7} \\
\text{fsy14a} & \\
\text{fsx20a} & \quad \text{inverted coordinates of FS = 2.0 curve, Fig 2.7} \\
\text{fsy20a} & \\
\text{fsx30a} & \quad \text{inverted coordinates of FS = 3.0 curve, Fig 2.7} \\
\text{fsy30a} & \\
\text{asx} & \quad \text{coordinates of alfa - s curve (Mana & Clough)} \\
\text{asy} & \\
\text{asxa} & \quad \text{inverted coordinates of alfa - s curve} \\
\text{asya} & \\
\text{adx} & \quad \text{coordinates of alfa - d curve (Mana & Clough)} \\
\text{ady} & \\
\text{abx} & \quad \text{coordinates of alfa - b curve (Mana & Clough)} \\
\text{aby} & \\
\text{g10x} & \quad \text{coordinates of FS = 1.0 in Figure 2.10} \\
\text{g10y} & \\
\text{g15x} & \quad \text{coordinates of FS = 1.5 in Figure 2.10} \\
\text{g15y} & \\
\text{f10x} & \quad \text{coordinates of FS = 1.0 in Figure 2.11} \\
\text{f10y} & \\
\text{f13x} & \quad \text{coordinates of FS = 1.3 in Figure 2.11} \\
\text{g13y} & \\
\text{f17x} & \quad \text{coordinates of FS = 1.7 in Figure 2.11} \\
\text{f17y} & \\
\text{f22x} & \quad \text{coordinates of FS = 2.2 in Figure 2.11} \\
\text{f22y} & \\
\text{f24x} & \quad \text{coordinates of FS = 2.4 in Figure 2.11} \\
\text{f24y} & 
\end{align*}
\]
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