International Conference on Case Histories in Geotechnical Engineering

(1993) - Third International Conference on Case Histories in Geotechnical Engineering

03 Jun 1993, 10:30 am - 12:30 pm

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Recommended Citation

Tamaro, Mark; Lopez, Pablo; and Pamukcu, Sibel, "Prediction of Structural Slurry Wall Behavior" (1993). *International Conference on Case Histories in Geotechnical Engineering*. 23.
https://scholarsmine.mst.edu/icchge/3icchge/3icchge-session05/23

Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, Paper No. 5.06

Prediction of Structural Slurry Wall Behavior

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SYNOPSIS The following study was undertaken with the intent of improving the ability to accurately predict the behavior of structural slurry walls. An existing wall, employed during the construction of the Washington D.C. subway system, was examined using four different analysis methods. The actual stresses and displacements of this wall were measured, providing a basis for investigating the accuracy of the different analysis techniques. The results obtained warrant the use of one particular approach, referred to in this study as the "Beam on Elastic Foundation Method". This method provided the most useful simulation of the soil/structure interaction that occurred during construction of the subway, in terms of accuracy and amount of work required.

INTRODUCTION

Structural slurry walls have become an increasingly popular method of supporting deep excavations in sites where large scale underpinning of adjacent structures would normally be required. They can be utilized as permanent structural components or as temporary retaining systems. The versatility of applications as well as efficiency of construction, often make these walls the most suitable retaining method during the construction of deep foundations, cut and cover tunnels, and deep vertical shafts.

HISTORICAL DEVELOPMENT

During the early 1900s bentonite mud slurry (sodium montmorillonite clay) began to be used for the construction of petroleum wells, serving a dual purpose of flushing drilling tailings to the surface, and providing circumferential support to the well walls. By the 1950s bentonite slurry was introduced as a means of supporting the excavation of deep trenches. In this application, the hydrostatic head and density of the slurry is maintained at a level which provides sufficient lateral support to prevent the side walls of the excavation from caving in.

Deep trenches constructed in this manner, are often used as cut-off walls and structural foundation walls. Cut-off walls refer to subgrade barriers constructed for the purpose of controlling ground water flow or pollution migration, where the slurry filled trench is backfilled with low permeability material. This type of wall is well suited for containing contaminated ground water, encapsulating land fills, and repair of earth dams.

Structural slurry walls are generally used as retaining systems during the construction of subgrade structures. These walls are constructed by installing reinforcing steel cages into slurry filled trenches followed by the displacement of slurry through placement of concrete. An example of the typical stages of construction for a structural slurry wall are presented in figure 1.

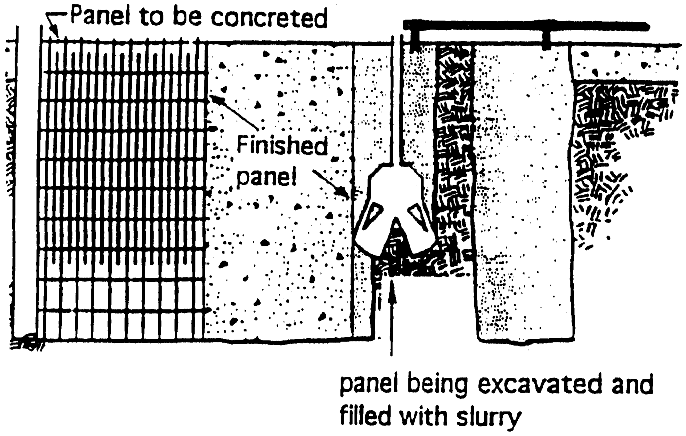


Figure 1. Slurry wall construction sequence

Structural slurry walls were first used during the late 1940s in Milan Italy, where they were incorporated into the construction of subway tunnels and deep building foundations (Kyle, 1967).

Presently, slurry wall technology has developed to the point where it competes with more conventional retaining methods, such as sheet piling or soldier beam and lagging systems (Kapp, 1969). In many cases, structural slurry walls have proven to be the most economical method of construction, and occasionally, the only feasible option.

METHOD OF CONSTRUCTION

Structural slurry walls follow a general construction scheme as outlined below.

1.) Slot trenches are dug along the perimeter of the proposed excavation. During excavation, bentonite slurry is continually pumped into the open trench, maintaining a hydrostatic head at least several feet above the ground water table.
2.) When the trench is excavated to its final depth, reinforcement cages, consisting of reinforcing bars and/or steel beams, are lowered into place, forming panels. When vertical steel beams are not used, stop-end devices are implemented to form the joints that separate panels. Concrete is then tremmied into each panel, displacing the slurry upwards where it is pumped out and cleaned for re-use.
3.) After the wall is completed, excavation begins within the perimeter of the wall. The excavation is performed in stages, where each stage is completed by placing tie-back or strut supports at levels specified in the design.

BENEFITS OF STRUCTURAL SLURRY WALLS

Slurry walls have dramatic benefits over conventional retaining methods when applied in several specific cases. For example, slurry walls are commonly used in areas where ground water tables are high. The advantage of using an impermeable concrete wall versus soldier beams and timber lagging is often exhibited in the reduced cost of de-watering the site, and the protection of adjacent structures. A site enclosed by a concrete slurry wall requires little dewatering and the surrounding ground water table is usually maintained at its normal level. In contrast, an excavation supported by a soldier pile and timber lagging system may encounter significant dewatering problems as well as possible settlement of surrounding structures due to draw-down of the natural water table. Slurry walls are also well suited for projects that require deep excavations. The depth of a slurry wall is usually controlled by the limitations of the trenching equipment, therefore walls can be constructed to depths well beyond 100 feet, provided the proper equipment is used. Slurry walls also prevail in situations where construction noise and vibration must not exceed a certain level (e.g. in urban locations where adjacent buildings are occupied). In these cases, the noise and vibration generated from driving sheeting or soldier beams can not be tolerated.

The use of structural slurry walls also eliminates the need for underpinning of adjacent structures. Often, when sheet pile retaining systems are used, elaborate underpinning schemes must be developed in order to avoid vertical settlements resulting from the horizontal deformations of flexible steel sheeting.

Lastly, slurry walls can be designed to remain as the perimeter walls of substructures (e.g. basement walls of buildings). In these cases the temporary struts can be replaced by subgrade floor beams, and the wall can be designed to act as a vertical load bearing element.

CURRENT DESIGN METHODS

Presently in the U.S., there are no specific codes or standards in existence that directly regulate the design of structural slurry walls. Design engineers currently use geotechnical design guides originally developed for flexible retaining systems to determine the loading and boundary conditions for a given wall. Structural codes (ACI and AISC) are then used to satisfy the strength requirements of the proposed walls. Currently used methods are either analogous to classical retaining wall design methods, or are modified versions of the classical approach. However, two methods studied in this paper differ from the standard design procedures, as they attempt to simulate the interaction between the structural slurry wall and the soil (soil/structure interaction). Four analysis methods, ranging from simple empirical techniques to highly sophisticated models were compared in this paper. Descriptions of these four methods follow.

Terzaghi-Peck Method (Bowles, 1988)

This is the most elementary method of analysis available. It was developed for the design of bracing where the soil conditions were uniform sand or clay and the water table was below subgrade. The analysis sequence is as follows. First, the active lateral earth pressure on the wall is determined using Rankine or Coulomb theory (Bowles, 1988). The maximum ordinate of the lateral pressure is then multiplied by an appropriate factor. This value of pressure is distributed as a uniform or trapezoidal loading, depending on whether the material being supported is sand or clay. A typical wall configuration and associated loading for granular backfill is shown in figure 2. A simple support is assumed at the level of subgrade, where the rotational restraints are released, leaving the wall to be analyzed as a series of simple-beams, or as a continuous indeterminate beam.

Although this method is commonly used to determine the maximum bending moment in a proposed wall, it was originally intended to be used for estimating maximum strut loads.

Net Pressure Method with Support Settlements (Tamaro & Kerr, 1990)

In this approach, the designer determines the Rankine active pressure along the entire length of the wall, as well as the passive pressure beginning at subgrade for each stage of excavation. The net pressure resulting from the superposition of the active and passive pressures then represents the lateral loading on the wall. The point where the net pressure initially reaches zero, is taken to be the point of zero moment (assuming there is sufficient passive pressure developed). The wall is truncated beyond this point and a simple support is assumed. As the excavation

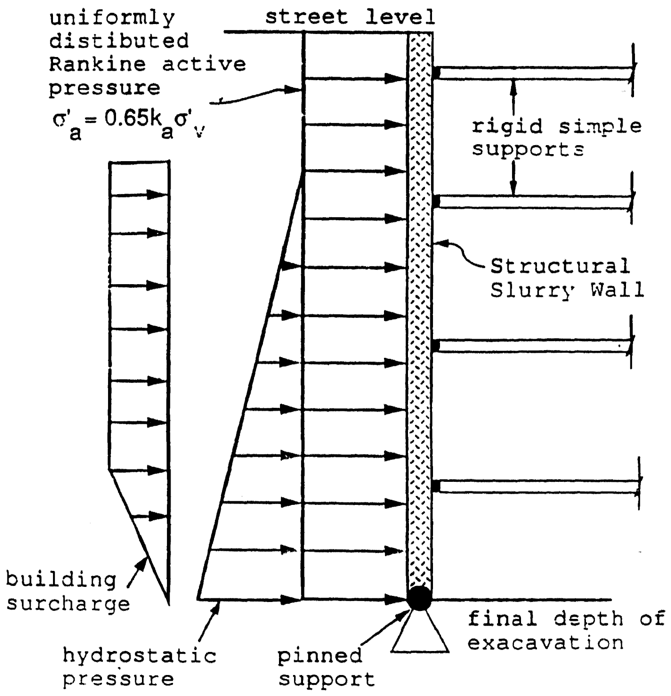


Figure 2. Terzaghi-Peck Method

stages progress and braces are installed, the wall is then analyzed as a continuous beam. The passive pressure is recalculated for each excavation stage prior to placement of the next brace, requiring the net pressure to be updated as well. The critical moment is then determined from the analysis of each stage, and the wall is designed accordingly.

The effect of wall movements are also addressed in this method. During the first stage, the wall displacement is determined at the depth where the future brace is to be placed. In the next stage the brace is installed with this displacement introduced as a support settlement. This process is continued for each of the remaining stages as illustrated in figure 3. By incorporating these initial displacements into the model, a more accurate prediction of the distribution of moments along the depth of the wall is obtained.

Beam on Elastic Foundation Method (Haliburton, 1979)

The Beam on Elastic Foundation approach is unique in that it utilizes springs to simulate both the elastic and inelastic behavior of the subgrade soils. Using this technique, the wall is loaded by Rankine or Coulomb active pressure on the unexcavated side while the subgrade reaction on the excavated side is simulated by at-rest pressure and a series of springs whose stiffness is equivalent to the subgrade modulus. A typical wall subjected to these oading conditions is shown in figure 4.

Similar to the previous method, the braces or tie-backs are modeled as elastic springs, and

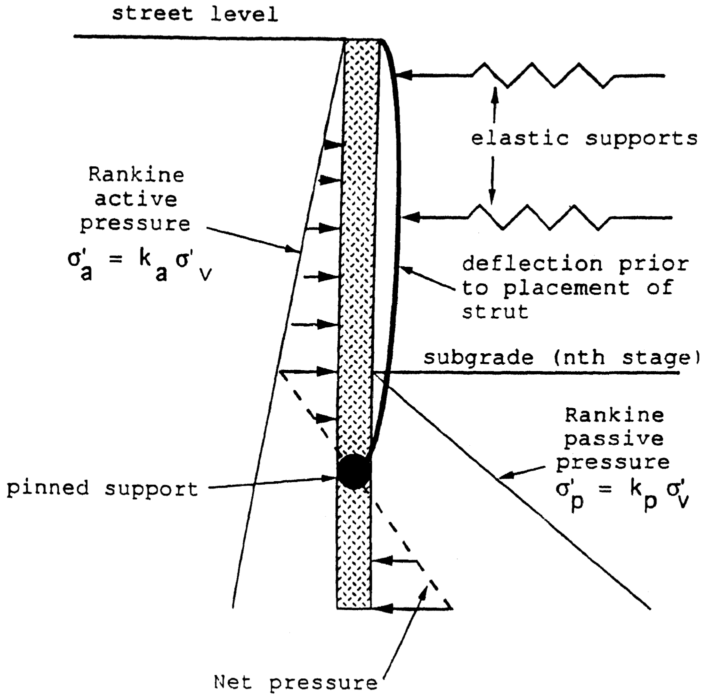


Figure 3. Net Pressure with Support Settlements Method

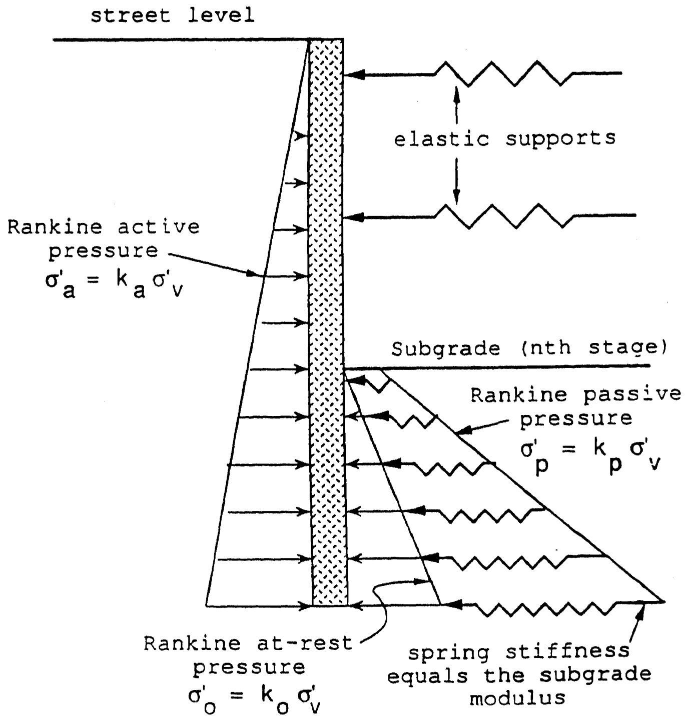


Figure 4. Beam on Elastic Foundation Method

the displacements that develop in each stage are superimposed on the subsequent stages.

This method also incorporates the concept of limit analysis in that the springs that form the subgrade reaction can be limited in capacity (the magnitude of the spring reactions is set as an upper bound equal to the subgrade passive pressure), thereby acting in a manner similar to the plastic behavior of the subgrade soil. For example, during the course of a solution iteration, if the reaction force in a spring exceeds the passive limit (yielded spring), the model is revised by removing the yielded spring and applying its passive limit as a load. This logic is continued along the length of the wall until the springs no longer yield. The repetitive nature of this analysis makes the use of an iterative computer program a necessity for obtaining a quick solution.

In addition to the complexity of the analysis, another potential problem arises when using this method. The designer must use a realistic value for the subgrade modulus (spring stiffness). If the value selected or computed is mis-representative of the actual soil behavior, the accuracy of the solution will be compromised. This is especially true when determining the deflected shape of the wall.

Finite Element Method (Filz, 1990)

Use of a two dimensional finite element mesh to model a plane slicing through a section of both the structural wall and the soil surrounding it provides two improvements over the previously mentioned methods. Most importantly, it allows the soil to be modeled using properties that are determined from tests of actual soil samples from the site. This eliminates the need for making assumptions such as equating the passive resistance to spring reactions or setting a fictitious subgrade point reaction. It also provides the user with resulting vertical displacements of the soil surface adjacent to the wall. This feature is unique to the Finite Element Method, as it is the only method which includes interaction of the surrounding soil.

DETERMINATION OF BEHAVIOR OF EXISTING WALL

It is necessary to determine several parameters before analyzing a wall using the methods discussed in the previous section. The existing soil parameters, lateral loading on the wall, flexural stiffness of the wall, and the stiffness of the support members must all be estimated. Approaches taken, and assumptions made during the calculation of the above parameters associated with the wall analyzed in this comparative study, are presented below.

Soil Parameters

Values for the angle of internal friction, cohesion, and unit weight of the soil at the site under investigation, were estimated from the original soil samples prior to construction.

Stress-strain characteristics, as well as, strength and bulk modulus values had to be approximated by using previously documented values of samples with similar soil classifications, due to the lack of triaxial test data (Duncan, 1980).

Wall Loading

The loading scheme applied on the unexcavate side of the wall included three components. These were the lateral earth pressure, the hydrostatic groundwater pressure, and the lateral component of the bearing pressure of adjacent building foundation.

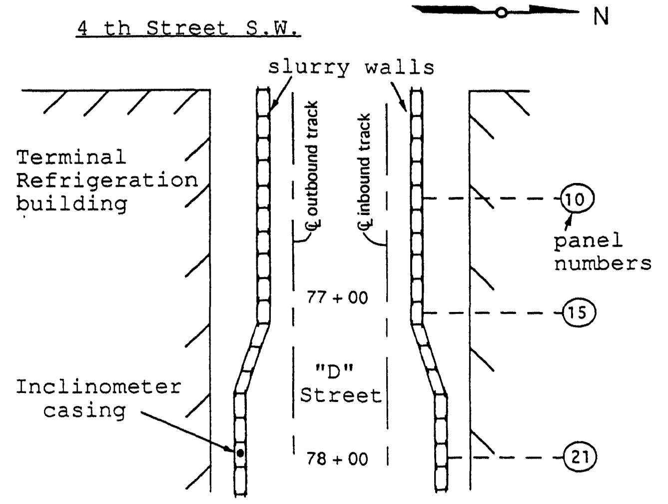
The lateral earth pressure was determined using Rankine theory (Bowles, 1988), where t effective vertical stress is multiplied by a coefficient representing either the active o passive lateral pressure. Wall friction was considered during the computation of the Rankine coefficients of lateral earth pressu This resulted in lateral earth pressures bei dependent on the angle of internal friction cohesion for each soil stratum.

Typical hydrostatic pressures were include in the analyses at depths which remained constant on the unexcavated side of the wall and varied on the excavated side for the different construction stages.

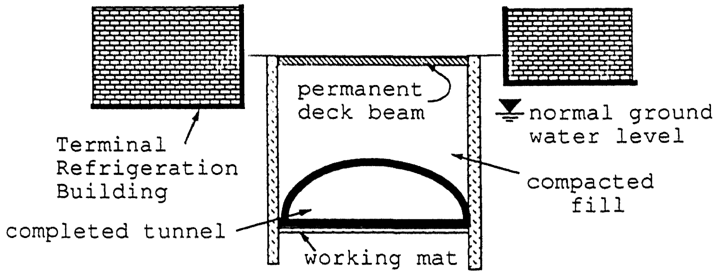
Lastly, the surcharge loading created by a adjacent building foundation was taken from original project specifications provided by Washington Metropolitan Area Transit Authori This loading was trapezoidal in shape, beginning at the base of the building foundation (twenty feet below the ground surface) at a magnitude of 1.2 kips per squa foot over a depth of sixty feet. From a dep of sixty feet to eighty four feet the load decreased linearly from 1.2 kips per square foot to 0 kips per square foot. These press diagrams were combined by superposition to f one loading diagram, applied per horizontal foot of wall.

Active loads calculated in this manner wer used for the analyses of the Net Pressure wi Support Settlements and the Beam on Elastic Foundation Methods. For the Terzaghi-Peck Method the magnitude of the active soil pressure calculated at the base of the wall reduced by a factor of 0.65 as suggested by Bowles, (1988). This adjusted soil pressure was distributed evenly along the length of t wall, while the building surcharge and hydrostatic pressures were superimposed as additional loads.

For the Net Pressure with Support Settleme and the Beam on Elastic Foundation solutions the subgrade passive pressure was determined for each excavation stage. Rankine theory w used to estimate the passive resistance on t excavated side of the wall. During the last two excavation stages the high shear strengt of the over-consolidated clay layers were included in the calculation of the passive pressure because they added substantially to the passive resistance of the subgrade soils. It was also assumed that during construction the excavation was de-watered to a level two feet below subgrade at each stage.



Plan View



X - Section

Figure 5. Slurry wall site

Subsurface Site Conditions

The site conditions of the Federal Center project were representative of the typical conditions for which structural slurry walls are best suited. The specific features were a high water table, a sub-stratum layer of low permeability high bearing capacity soils, and a site surrounded by structures highly sensitive to settlement.

Boring samples taken at the site described the geological profile as a thin layer of fill, followed by several layers of compact, medium to coarse sand, and two layers of dense over-consolidated clay located approximately sixty to ninety feet below street level as shown in figure 6.

The two clay layers had sufficient bearing capacity to support the vertical loads from the walls, while their relatively high shear strengths provided significant passive resistance at the base of the wall. The clay layers also acted as an impermeable layer essential for limiting groundwater from flowing under the base of the wall and into the excavated area.

The natural water table, was located twenty two feet below street level. Variations in the water level, particularly draw-down associated with dewatering the excavation, could have caused an increase in the effective vertical stresses. If the increased stress exceeded the pre-consolidation stress in the lower clay strata, consolidation and settlement would occur. The occurrence of differential settlement in areas adjacent to the site would have had profound effects on the existing concrete and masonry buildings including severe cracking and possible structural failure.

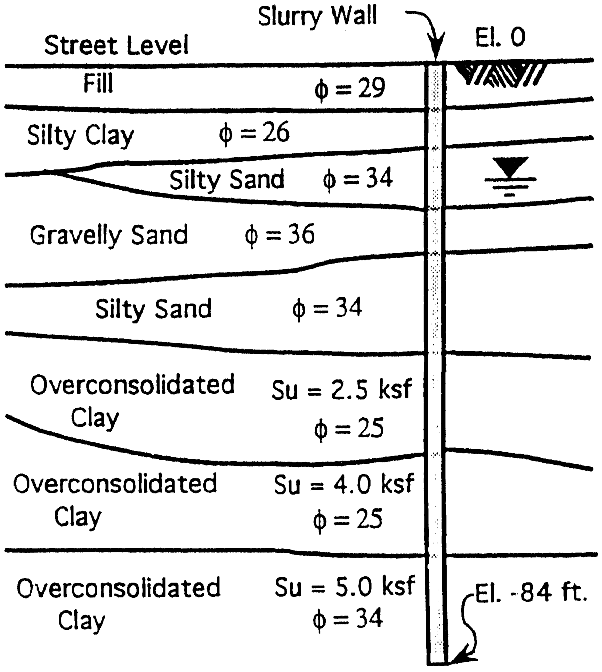


Figure 6. Soil Profile

Wall Construction

Two parallel slurry walls were installed seventy feet apart, extending to a maximum depth of eighty four feet and are approximately eleven hundred feet long in plan. Occupied buildings were located near the walls along both sides of the excavation, leaving little room for construction equipment and requiring strict control of ground settlements associated with horizontal wall movements. These buildings imposed surcharge loads on the walls in addition to typical horizontal earth and hydrostatic pressures.

Both walls were constructed as a series of seven foot long panels separated by steel soldier beams. A trench was excavated for each panel using a special thirty two inch wide, nine ton clamshell bucket followed by the placement of W30 x 211 soldier beams, connected by a reinforcing cage, at each end of the trench. Concrete was then placed into the trench by tremie methods, forming a series of separate panels. After completion of the wall panels, the excavation was advanced in five stages.

Initially, the subgrade level was lowered to a depth two feet below the position of the first set of struts to be installed. At this level, the struts were placed and excavation continued to a depth two feet below the next experience with similar projects and empirical relationships, or limited by the serviceability of the wall.

Beam on Elastic Foundation Method

The Beam on Elastic Foundation Method, produced conservative moment values. It resulted in critical moments that were of the same magnitude, or larger than the measured moments in the wall for both positive and negative wall bending. Use of this method for determining maximum moments should yield a safe design. However, obtaining a solution requires the ability to perform a sophisticated computer analysis.

Finite Element Method

The moments produced by the Finite Element analysis were more conservative than the Beam on Elastic Foundation Method. The increase in the moment values is mainly attributed to an underestimation of the passive soil strength. Use of these values would also produce a safe design. However, these results would produce an "over designed" wall leading to higher construction costs.

The moments from this method also exemplify a major shortcoming of this analysis technique. The solution proved to be highly sensitive to inaccuracies of the soil element properties. Large amounts of time spent on achieving a solution may not be warranted due to this sensitivity.

Geotechnical Conclusions

The geotechnical engineer is mainly concerned with the settlement of structures adjacent to the excavation site. These settlements are caused by disturbances in the soil beneath neighboring structures, such as a reduction of the groundwater table, or lateral soil movements. Structural slurry walls have proven to be successful in maintaining the level of the local water table, but excessive wall movements must be controlled to assure the safety of surrounding structures. With this in mind, the analysis methods were judged on their ability to accurately predict the wall movements throughout the excavation process.

Terzaghi-Peck Method

The Terzaghi-Peck Method is unsuitable for determining deflections of slurry walls that are constructed with more than one level of bracing. This method does not consider the fact that walls can accumulate displacements prior to placement of braces, or that rigid body movements can occur.

Net Pressure with Support Settlements Method

The results obtained from this study indicate that the Net Pressure with Support Settlements Method under-estimates the lateral wall movements for the last two stages of excavation. The deflections exhibited in th stages leading up to this point, do however, appear to provide an adequate approximation the actual measured values. The discrepanci that occur in the late stages may be explain by considering the accumulating effect of under-estimated support settlements on the over-all deflected shape. When the initial computed deflections are lower than the actu deflections, the introduction of these valu as support settlements over a series of stag can compound the errors. To minimize the effect of this problem, the model could be r analyzed with increased support settlements, thus assuring that the predicted deflections would be conservative.

Beam on Elastic Foundation Method

The Beam on Elastic Foundation Method produc conservative deflection values for all stage In addition, this method addresses the possibility of deflections below subgrade. This not only contributes to the conservativ nature of the solution, but also identifies instability conditions at the base of the wa by displaying excessive base movements. The results obtained by using this method can be improved by varying the flexural stiffness along the depth of the wall. This allows th designer to use the "gross" moment of inerti along segments of the wall that are subjecte to low stress levels, while using the "crack moment of inertia along wall segments that undergo stresses sufficient to produce tensi cracking in the concrete. However, it is important to note that such refinements may be justified until more accurate estimates o subgrade moduli can be developed.

Finite Element Method

As previously mentioned, the Finite Element solution was adversely affected by inaccurat soil properties. In terms of lateral deflections this resulted in a translational movement at the base of the wall of one inch, as shown in figure 9. This horizontal translation magnified the deflections due to bending over the remainder of the wall. Because the measured deflection of the actua wall showed no movement at the base, it can concluded that the Finite Element results ar dubious.

Although this solution proved to be unreliable, the time spent on the Finite Element Method may be justified by the fact that it does produce the values of vertical displacements adjacent to the wall. In this study settlement under the adjacent building amounted to one inch, approximately uniform along the base of the building. This information is valuable but dependent on accurate soil information.

CONCLUDING REMARKS

This study was undertaken in order to improve the understanding of how a structural slurry

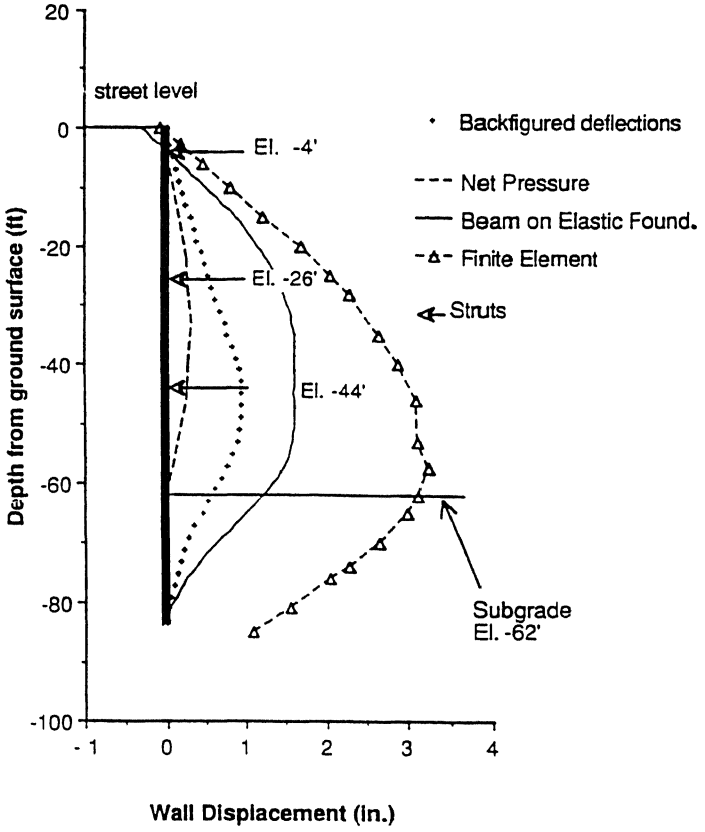


Figure 9. Deflection Comparison

wall behaves when constructed in a manner similar to the procedures followed in this example. For the wall under investigation, it is apparent that the major differences between the analyzed behavior and the actual behavior of the wall can be attributed to an incorrect prediction of the inward displacements of the wall prior to the placement of brace levels. This most likely has caused inaccuracies resulting in under-conservative, or critical predictions in the Terzaghi-Peck and Net Pressure models. The Beam on Elastic Foundation and Finite Element Methods both allowed the base of the wall to displace laterally, and in most stages produced conservative deflection and moments in the wall. However, the Finite Element Method's sensitivity to soil parameters precludes its use unless reliable triaxial test results for the appropriate load ranges are available. Therefore, it can be concluded that the use of the Beam on Elastic Foundation Method is the most reliable method of analysis among the four approaches under investigation for designing structural slurry walls. However, in the absence of a computer program capable of determining a solution to this model, the Net Pressure with Support Settlements Method could be used to attain a safe design, provided that a range of initial support settlements are analyzed.

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