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## **Deep Underground Basements for Major Urban Building Construction**

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## **DEEP UNDERGROUND BASEMENTS FOR MAJOR URBAN BUILDING CONSTRUCTION**

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**ABSTRACT:** Deep underground basements that are integrated into urban development projects early in the overall project design offer many inherent improvements to the overall quality and value of the project and its surrounding community. Diaphragm walls combine into a single foundation unit the functions of temporary shoring, permanent basement walls, hydraulic cutoff, and vertical support elements/shear walls, and, because of this combination, have proven to be an economical alternative in many circumstances. This paper examines the evolution of deep underground basement construction, identifies considerations associated with diaphragm wall construction, and provides several case history examples to illustrate the resolution of key issues.

### **INTRODUCTION**

Today, deep underground basements are an important component of new urban building construction. This is often because parking in most large cities is generally inadequate and often serviced by aging, outdated, and deteriorated above-grade parking structures that do not fit the surrounding architecture and occupy valuable aboveground space. The integration of underground parking into major, new building projects in urban environments can enhance the aesthetic and economic values of the overall development.

Conventional basement construction practices have evolved from drivers that include:

- Economy
- Local expertise
- Local tradition
- Local geology
- Groundwater
- Site right-of-way

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## **Evolution of Excavation Support Systems**

### *Open Cuts*

When space is available, the most economical way to build a permanent basement is often to construct the foundation in an open cut excavation. This requires sufficient right of way to construct safe slopes and access to excavation, dewatering, and backfill construction expertise. Limitations associated with an open cut solution are typically a construction site with restricted laydown areas far away from the building footprint, restricted crane access, and a need for dewatering. The latter is often associated with detrimental settlements of surrounding properties. In addition, the costs associated with handling, managing, and replacing the large volumes of earth located outside the building footprint increase rapidly as the excavations become deeper.

### *Soil Nailing*

Soil nailing as temporary shoring is a relatively recent technique, introduced in the mid 1980s, which works very well under a specific set of conditions. These include stiff soils, adequate lateral right-of-way, no utilities at the perimeter below a depth of about 6 feet, and no running soils or water inflow issues. These are conditions that are somewhat ideal and not common in most major urban areas. As a consequence, soil nailing is not a widely used urban temporary shoring technique except in specific locales such as Seattle. Examples of successful soil-nailed temporary walls include those completed with a final shotcrete or cast-in-place concrete facing, and with the permanent lateral support provided by the basement floor system.

### *Soldier Piles and Lagging*

Driven or drilled soldier piles, with wood or shotcrete lagging, supported by either drilled tiebacks (soil/rock anchors) or internal bracing supporting the piles are a simple temporary shoring type with a long history of usage in urban foundation construction. In many conditions with stiff soils, it is economical and safe. However, many urban centers in the United States are underlain by permeable soils with a high local groundwater table, particularly when compared to the depth of excavation required to provide needed parking. Soldier piles and lagging is a permeable wall system, and often accompanied by a lowering of the surrounding groundwater table. In addition, ground losses and raveling during lagging installation are inherent risks when using this system. Altering the water table around a deep excavation can cause elastic displacements of granular soils and consolidation settlements of clay or silt soils. Ground losses and raveling are also a source of settlement. If the surrounding buildings and their occupants cannot tolerate or are sensitive to the resulting settlements, then a shoring system that permits better water and ground loss control is warranted.

A second issue with soldier pile and lagging systems is that they are typically designed and constructed separate and independent of the permanent structure. They can serve as a back form for the permanent concrete basement walls, but the soldier piles are not easily integrated into the permanent structure. Most commonly, soldier pile and lagging walls are constructed 4 to 5 feet outside of the basement line to accommodate the double-sided concrete wall forms and the placement of an exterior waterproofing membrane. As a consequence, the impacts of construction at or outside of the property line must be considered. Impacts may include utility interference and additional excavation/backfill. Regardless, in cities with predominantly granular soils and a high groundwater table, soldier pile and lagging walls are not practical and are seldom used.

#### *Tangent Auger Cast Piles or Tangent/Secant Drilled Shafts*

Where running soils preclude the use of spaced soldier piles, tangent or secant walls made of auger cast in place piles (ACIPP) or drilled shafts can be used. Although ACIPP walls and tangent drilled shaft walls are not fully impermeable, they can be quickly excavated without major ground losses, except in the most severe conditions. A well constructed secant wall made of drilled shafts can result in a relatively water tight wall. To do this, softer concrete lagging shafts are used, and then cut into and bonded together with structural soldier piles that are designed like soldier piles.

#### *Interlocking Steel Sheet Piles*

Interlocking sheet piles have been used historically to shore excavations in granular soils below the water table, particularly when they can be toed into a relatively impermeable layer. However, a braced or anchored sheet pile wall excavation support system also requires a separate concrete basement structure. This structure needs to be designed to resist the uplift pressures from the surrounding groundwater table. If an underdrain system is used, long-term pumping can be very costly, and there is likely a permanent lowering of the surrounding groundwater table. The latter may result in settlements and possible deterioration of foundation elements such as timber piles. Many urban sites are not amenable to driven sheets due to obstructions, natural (boulders) and anthropogenic (utilities, miscellaneous fills, and remnants of prior construction), or vibration sensitive surroundings where building damage or settlements due to driving are an issue.

#### *Soil Mixing Walls*

Many of the advantages of a sheet pile wall system can be gained by constructing a soil mixed wall reinforced with closely spaced steel soldier piles (Pearlman and Himick, 1993). This is accompanied by the added benefits of a stiffer wall system and substantial reductions in vibrations during the temporary

excavation support wall installation. However, the issues associated with the design and the construction of a permanent wall system remain. Installation of a soil mixed wall temporary excavation support system requires large equipment, and substantial spoils, that must be managed and removed for disposal, are generated during construction

### *Concrete Diaphragm (Slurry) Walls*

Concrete diaphragm slurry walls were first introduced in the United States in the 1960s, and have found a niche in certain urban centers (such as Boston, MA). They are often attractive in granular soils with a high groundwater level and low permeability soils that underlie the granular soils that can serve as a cutoff; in areas with very dense and historic urban infrastructure; and where there exists a healthy demand for underground parking under buildings. Diaphragm walls are excavated through bentonite slurry using specially fabricated rectangular clamshell buckets to construct concrete panels of planned dimensions. After a panel excavation is completed, a carefully fabricated three-dimensional reinforcing cage is inserted into the panel excavation. Concrete is then placed around the reinforcing using tremie methods to form each concrete panel.

Permanent concrete diaphragm (slurry) walls are an ideal solution for structures requiring deep basements, particularly where a high groundwater table is present. Concrete diaphragm walls provide the following advantages for urban construction:

- Temporary and permanent groundwater cutoff
- Zero lot line construction
- Stiff structural capacity and superior resistance to movements
- Easily adapted to both anchors and internal structural bracing systems
- Expedited construction, because only interior columns and slabs need to be built.

Slurry wall installation requires sufficient work area to set up the slurry plant (desanders, etc.) as well as additional space to assemble the reinforcing cages prior to placement in the wall. Hence, this work may be difficult on congested sites.

Compared to wall types described above, diaphragm walls are considered to be very stiff with respect to ground movement control (Clough and O'Rourke, 1990). Diaphragm walls are very amenable to a wide variety of ground conditions, and can be reinforced to allow incorporation of many structural configurations.

### **Demonstration of the Art**

This paper discusses aspects of three successful projects with deep basements constructed in congested urban environments and the design approach that the authors developed and applied to these projects. The specific projects include 10 St. James in Boston's Back Bay, the new Harvard Medical School Research Facility in Boston, and the U.S. Capitol Visitor Center in Washington D.C.

All three projects are constructed adjacent to and below foundations supporting significant structures. In addition to designing for the earth and water pressure loadings, the appropriate consideration and modeling of surcharges and their effects are paramount for successful movement control by the excavation support system.

The 10 St. James project in Boston's Back Bay included excavation of narrow diaphragm wall panels directly adjacent to and below belled caissons supported with end bearing loads of 5 ksf. At the U.S. Capitol Visitor Center, a diaphragm wall excavation is constructed within 2 feet of the footings for the east front of the Capitol Building, with excavation to 50 feet below the existing grade. The 10 St. James project used internal cross-lot and corner braces, whereas the Harvard Medical School project used two types of support: an internal bracing system in a deep, constrained area at the end of the site; and tiebacks elsewhere. The U.S. Capitol project utilizes high capacity soil anchors to support the slurry wall.

The three project case histories are discussed, the design methodologies for the walls and wall support systems are described, and the movement performance is reviewed.

## **DESIGN METHODOLOGIES**

The design analyses for excavation support systems can range from relatively simple empirical analyses to more complex computer analyses, where typically all stages of the excavation sequence are evaluated. The design considerations should include not only the stresses and loads on the support system, but also the affect of construction movements on the response of adjacent structures. The level of effort for the evaluation often depends on the stage of the project, proximity of structures, contractor's methods of construction, and known local practice. Our discussion of design methodologies will consider both structure loading and system movements.

### **Empirical Methods**

#### *Stress Analysis*

Traditionally, apparent pressure envelope methods have been used successfully to design flexible wall systems such as soldier pile and lagging and steel sheet-pile systems. The approach was developed based on data from flexible wall systems, and typically assumes that the wall acts as a simple beam spanning between the brace levels (Terzaghi et al., 1996). For the more rigid slurry wall system, the pattern of wall displacement that develops during the actual excavation and bracing sequence can have a major effect on the bending moments in the wall and the distribution of load to the bracing/anchors. Hence, use of apparent pressure envelopes for design of stiffer systems can be misleading. In general, apparent pressure envelope loadings are most appropriate as upper

bounds for cases that match the bases of the empirical data, which include cases with relatively flexible walls and a stable subgrade.

The pressure envelope design approach is for a temporary support system and does not necessarily provide the long-term loading corresponding to the permanent condition after the end of excavation. When the temporary support system, such as a slurry wall system, is incorporated into the permanent building foundation, a staged analysis that includes loading at each stage is required to evaluate the built-in stresses and strains that are locked into the final structure at the end of construction.

### *Movement Analysis*

The use of empirical data for the evaluations of movements is a useful tool in evaluating potential effects of a proposed excavation on adjacent buildings. Empirical data also allow the designer to validate the general magnitudes and patterns of the results of more sophisticated analyses. The empirical data can be used to estimate the zone of influence of the excavation as well as typical magnitudes of ground movements for various wall stiffness and subgrade stability conditions (e.g., Clough and O'Rourke, 1990).

### **Staged Excavation Analysis**

Staged excavation analyses use numerical approaches to model the actual sequence of excavation and brace installation by considering each stage of the excavation as it is constructed, and the excavation support is installed and then removed. The soil and water pressures applied to the wall are representative of the actual pressures (not apparent pressure envelopes) expected in the system at each stage, and calculated loads are representative of the actual loads (not upper bound loads). The models can incorporate interaction of the soil and the structure as the earth pressures vary with displacement. The overall reliability of the structural requirements and displacement performance estimates determined from a staged excavation analysis is directly related to and very sensitive to the quality of the input parameters, particularly soil stiffness parameters.

Three general methods have been used for staged construction analyses:

- Equivalent Beam Method
- Beam on Elastic Foundation Method
- Finite Element Method

The equivalent beam method is outdated and rarely used in current practice. Our discussion will focus on the beam on elastic foundation and finite element methods. Both approaches can be used to predict stresses, loads, and system movements.

### *Beam on Elastic Foundation Method (BEF)*

The earth pressures are modeled with a series of independent spring supports (Winkler elastic foundation model). At the start of the model, the springs are compressed to create an initial load equal to represent a state of at-rest pressure. At each stage of excavation or support system, the spring loads change as soil, water, and support system loads are applied or removed and lateral wall displacement occurs. The soil springs load-displacement relationship (modulus of subgrade reaction) is determined by the input soil stiffness and governs the spring displacement until the limiting value of active or passive pressure is reached.

The Winkler elastic foundation model approximates the wall-soil interaction with a one-dimensional model instead of a two-dimensional model that includes the soil mass, and hence does not include the effects of arching within the soil mass.

Typically, the required soil parameters include: unit weight; at-rest, active, and passive earth pressure coefficients; and values for the modulus of subgrade reaction for the various soils that may affect the system. The modulus of subgrade reaction is not a true soil property, but rather depends on both the soil conditions and the geometry of the excavation being modeled. To be representative, the modulus of subgrade reaction needs to be adjusted based on the effective influence zone, which varies with the size of the loaded area.

Typically, the predicted wall displacements are much more sensitive to the values of subgrade modulus used in the analysis than the predicted brace loads and wall bending moments. Hence, conservative selection of the modulus of subgrade values should provide conservative estimates of ground movements, without significantly increasing the structural demand of the wall and bracing system.

The BEF method does not directly estimate ground movements behind the wall. Ground movements behind the wall are evaluated using the calculated wall displacement from the model. An empirical relationship between wall movement and ground movements must then be used.

There are several computer programs that automate the analysis. Some use Young's modulus as input for the soil stiffness. The program then automatically converts the Young's modulus values for the various soils to adjusted values of subgrade reaction modulus using closed-form elastic solutions.

The BEF analytical model can provide useful insights into the behavior of the wall and the wall-soil boundary, and the automated computer programs make it easy to perform multiple analyses for optimizing the design and evaluating sensitivity to input parameters.

### *Finite Element Methods (FE)*

Finite element models are typically two-dimensional models that include the soil mass surrounding the excavation. The stress-strain response of the soil is represented by a mathematical soil model that can vary from a simple linear-elastic model to a complex nonlinear elasto-plastic model. The stress-strain response can be defined in terms of effective stresses or total stresses. The required input parameters depend on the soil model used.

Generally, it is desirable to use a soil model that can model failure (plastic yield) when the soil strength is exceeded. In some problems, the ability to model volumetric changes in the soil (consolidation or dilation) may be important. A linear elastic, fully plastic Mohr-Coulomb soil model is often used. In this soil model, the soil acts linearly elastic until it reaches failure, defined by the Mohr-Coulomb criterion, where upon it becomes perfectly plastic.

In contrast to the BEF analysis, the FE analysis can provide direct information on the ground movements outside of and inside the excavation. It can also be used to model the soil-structure interaction response of nearby structures to the excavation-induced ground movements. In the past, performing FE analyses have been complex and time consuming to perform, but new, user-friendly programs (e.g., PLAXIS) are making their use more common. Another difference between the FE and BEF methods is that variations in the soil stiffness (modulus) can have a greater effect on predicted loadings and movements due to the inclusion of soil arching in the FE model.

FE models can be used to perform parametric studies to understand the relative effects of changes of parameters such as soil stiffness and excavation support stiffness and sequence on forces, stresses and displacements. They can also be used to estimate the absolute magnitudes and patterns of excavation support systems and ground movements which is much more difficult. A primary reason for the difficulty is the selection of reasonable stiffness values for the various materials that make up the soil mass. In general, values of stiffness based on laboratory and field tests tend to underestimate to a large degree the ground stiffness. This in turn can result in an overestimate of the magnitude of displacements, by two times or more, and the extent of the influence zone around an excavation. This tendency can be tempered to a great degree by using representative, local, field case history data during the selection of material parameters and to calibrate the numerical model to previous case histories.

### **CASE HISTORIES**

We will discuss three case histories where slurry wall excavation support systems have been incorporated as permanent foundation elements in the final structure. In all three cases, the walls provide groundwater cutoff, and the excavation penetrated below the bearing level of the foundations of the adjacent

buildings. The case studies will be used to illustrate design considerations for slurry wall systems as foundation elements. Nicholson Construction performed the wall construction and GEI Consultants provided design services on all three projects.

## **10 St. James Avenue**

### *Project Description*

10 St. James Avenue is a new 550,000-square-foot office complex constructed in Boston's Back Bay. The building includes a 19-story tower with a 280-foot-long by 170-foot-wide underground parking garage on 3-1/2 levels for 400 cars. The slurry wall excavation support system was included as the permanent basement wall, which was connected to a compensating mat foundation system, to create a watertight basement. Nicholson was engaged as a design-build package contractor with the responsibility for the site preparation, wall construction, mass excavation, lateral bracing, and waterproof concrete mat installation.



Overview of 10 St James foundation construction looking south from the Boylston Street side. Note excavation working to the north and the first mat placement has been installed in the center of the south wall

### *Design Considerations*

The excavation was 50 feet deep and penetrated through a stiff crust into the underlying soft clay layer. Immediately adjacent to the excavation were two, approximately 15-story office buildings, which were supported by deep foundations bearing in the stiff crust. Existing concrete and timber pile

foundation elements represented a challenge to the installation of the slurry wall along the property lines.

The analyses for the design of the support system were performed using a BEF model (WALLAP, 1997). During construction, additional modeling was performed to evaluate the affect of high bracing preloads on the wall stresses/movement performance, and to verify the initial design model using the actual construction sequence and the related instrumentation data.

### *Performance*

The proximity of the adjacent structures with their foundation system support located above the subgrade level of the excavation prompted the construction team to re-examine the sequence and staging of the work, to balance costs with mitigation of potential impacts on the surrounding buildings. As the performance of the system was confirmed by the instrumentation data, the construction sequence was adjusted to expedite construction of the base mat, which in turn further limited lateral movements of the wall by acting as a subgrade level brace.

Numerous wood piles were present in the northeast portion of the excavation. At the start of their removal in preparation for slurry panel construction, inclinometer data showed horizontal movements near the building in the range of  $\frac{3}{4}$  of an inch. This was approximately equal to the overall movements measured during the excavation construction. Revised procedures for the pile removal were then implemented to reduce overall movements of the buildings; however, it should be emphasized that site preparation and obstruction removal are activities that can create greater ground disturbance than the actual excavation sequence.

In general, the model movement predictions were conservative, especially for the cantilever excavation stage, where the predicted movements were two to three times larger than the measured movements. Assuming a 50 percent prestress in the bracing, the modeling predicted excavation wall movements on the order of 1.4 inches. During construction, a larger pre-load, to as much as 100 percent of the design load was employed, without adverse effects on the support system and the surrounding buildings and utilities. The result was excavation wall movements about half of those predicted (approx. 0.8 inch vs. 1.4 inches). When the models were rerun with the larger prestress, the calculated displacements more closely matched the measured wall displacements. It is also important to note that at the start of the construction, the design-build construction team performed additional field explorations and laboratory testing of the soil conditions at the site to determine input design parameters.

The authors' note that the literature suggests that there may be little value to using high values of prestress when using rigid bracing (O'Rourke, 1981). Using bracing loads closer to the total working load, as was done in this case, is uncommon and generally not necessary. If used, careful consideration needs to be made for possible overload due to temperature effects and load shifting, and

balanced against the benefits that an increased prestress may have on movement control. Certainly, when pre-loaded ground anchors are used, it is common practice to fully pre-load them to the fully anticipated design load, because their flexibility makes them less sensitive to load change with inward wall movement.

## **Harvard Medical School Research Facility**

### *Project Description*

One of the largest expansions to Harvard Medical School is a 430,000 SF biomedical research center shared by the medical school and affiliated hospital. Nicholson designed and constructed 123,000 SF (1,670 LF) of 2.5-foot-thick diaphragm wall composed of 84 panels with depths ranging from 65 ft to 93 ft; 178 temporary anchors (150-200 kips) and a temporary internal bracing system. A single row of tiebacks was installed in the shallow excavated area, while two levels of tiebacks and a third level of bracing were installed in the deepest areas.

The L-shaped structure consists of a 5-story building and a 10-story research tower. In addition, a 196,000 SF 2-level underground parking area to accommodate 500+ vehicles was built below the building. A deeper excavation under the research tower was required for mechanical equipment.

### *Design Considerations*

The slurry walls for the shallow portion of the excavation were supported by a single row of high capacity tiebacks. Tiebacks were also used for the upper level support of the deep portion of the excavation. The foundations of one of the adjoining buildings consisted of steel piles to rock, which was located below the excavation subgrade. The tight spacing of these piles presented a challenge for the design and construction of the tiebacks for the support system. The second adjacent building was founded on belled caissons bearing approximately 25 feet below the ground surface and approximately 30 feet above the subgrade elevation of the deep portion of the building. Control of movement of these foundations was considered key to limiting damage to the building.

The analyses for the design of the support system were performed using a beam on elastic foundation model (WALLAP, 1997). During construction, additional modeling was performed to evaluate as-built conditions and to evaluate the design based on the results of instrumentation data.

### *Performance*

The instrumentation data indicate that the wall performed better than was predicted by the model. In particular, the model over-estimated the cantilever movements of the wall by a factor of at least two. We note that for a variety of projects the cantilever case movement predictions from the model are higher than actual wall movements even when we get better agreement between the model predictions and actual movements for latter stages. Since the soil provides the

sole support of the wall in the cantilever case, and conservative soil parameters are used in the model, it is not surprising that the cantilever case predictions tend to be higher than the actual movements of the wall. During an intermediate stage of construction for the deep excavation (the stage just before final excavation to subgrade), the inclinometer data indicated that a portion of the deep excavation was deflecting more than predicted by the model or observed at inclinometers in other portions of the deep excavation.

Disturbed subgrade (traffic and excess pore pressures in the silty subgrade) was identified as the potential reason for the larger deflections. We revised the model to include the effects of the disturbed subgrade on the next to last and final excavation stage, and concluded that additional bracing was not required to complete the excavation within the allowable movement criteria for the project. Table 1 lists modeled and measured deflections at several locations along the wall heights for the original and revised models and the inclinometer data.

High capacity tiebacks were installed with their bond zone in an inter-bedded deposit of fine sand and silty clay. The anchors were sized for a typical design load of 200 kips. Post grouting was used to achieve this capacity

**Table 1. Modeled and Predicted Wall Movements**

Elevation (ft)	Model/Data	Movement of the Wall			
		Cantilever (in)	Stage 1 (in)	Stage 2 (in)	Final Stage (in)
+10	Original	0.28	0.36	0.10	-0.08
	Revised	0.42	0.53	0.24	0.06
	Inclinometer	0.1	0.6	1.0	
-3	Original	0.11	0.46	0.46	0.28
	Revised	0.17	0.55	0.61	0.37
	Inclinometer	0	0.7	1.4	
-15	Original	.06	0.4	0.68	0.77
	Revised	0.08	0.41	0.83	0.79
	Inclinometer	0	0.5	1.1	
-33	Original	0.05	0.28	0.55	1.4
	Revised	0.07	0.25	0.55	1.34
	Inclinometer	0	0.3	0.7	

## **United States Capitol Visitor Center**

### *Project Description*

The U.S. Capitol Visitor Center (CVC) is the largest addition ever made the Capitol Building in Washington, DC. The CVC building, 50 feet underground,

will front the entire East Front of the Capitol. The Capitol itself encompasses 775,000 SF, while the completed CVC will contain 580,000 SF on three levels. The CVC project footprint covers 193,000 SF, or approximately 5 acres, which is larger than the Capitol itself, whose footprint is 175,000 SF. Initial construction of the Capitol Building was in 1800.

The CVC will include space for exhibits, food service, two orientation theaters, an auditorium, gift shops, security, a service tunnel for truck loading and deliveries, mechanical facilities, storage, and much needed space for the House and Senate. When completed, the CVC will preserve and maximize public access to the Capitol, while greatly enhancing the experience for the millions who walk its historic corridors and experience its monumental spaces every year.



Excavation Support Wall Looking West  
Courtesy of the Architect of the Capitol

Nicholson Construction Company was hired by Centex Construction Company, a general contractor working for the architect of the Capitol for the Phase I Structure package of the project. Nicholson's work includes design and construction of the 2400-foot-long permanent walls of the addition using 130,000 SF of 32-inch-thick concrete diaphragm walls, 500 drilled anchors (typically 200 to 300 kips design load), and jet grouting to complete the water cut-off in areas where the diaphragm wall abuts existing structures or its installation is restricted by other conditions. The entire support of the excavation system consists of the combination of the diaphragm wall, temporary tiebacks, cross bracing, and jet-grouted cutoffs.

The original project bid documents included a scheme for installing drilled shafts with permanent building columns from the same working grade as the diaphragm wall construction. Once the roof structure was installed over the

columns, which was intended to act as an initial internal bracing level, then several rows of drilled anchors were to be installed along with the mass excavation. The mass excavation work was to occur under the deck while working around the pre-installed columns. Nicholson proposed to change the sequence of the work, allowing drilled shafts to be placed and columns erected from the final subgrade elevation. This eliminated the deck as an internal brace, but offered both economy and better site utilization. Extensive analyses, using both the BEF approach (WALLAP, 1997) and the FE approach (PLAXIS, 1998), were performed to verify that the alternative scheme would provide equivalent performance to the initial contract design.

### *Design Considerations*

The primary design concern for this project is to control and minimize movements of the existing Capitol Building. The diaphragm wall foundation was designed with this goal and to act as a permanent water cut-off and structural wall for the three-level underground structure.

The foundations for the Capitol are within two feet of the wall in some locations. The foundation bearing level and loading varies significantly across the structure, presenting a wide variety of potential load cases and analysis profiles.

The analyses for the structural design of the support system were performed using both BEF and FE models. The BEF program (WALLAP, 1997) was easier and quicker to run than FE programs, so it was used for the structural design of the wall system. By using the BEF model, the design team could evaluate more design profiles. Two FE models were run to verify that the BEF model loadings and stresses were conservative, and to provide ground deformation predictions to compare to contract requirements. Soil properties were selected based on geotechnical laboratory testing (Weidlinger Associates, Inc. 2001), as well as published values from test section case histories in the Washington D.C. area (O'Rourke, 1975).

### *Performance*

Figure 1 presents the predicted deflected shapes of the slurry wall for the BEF and FE model analyses, as well as inclinometer data for the most heavily loaded design sections. The FE model included the tieback anchors modeled within the soil mass. The difference between the movements predicted by the BEF model and the larger movements predicted by the FE model is essentially the free field movement behind the anchor zones of the tiebacks. In other words, the BEF and FE model had good agreement in predicting the local movement of the wall. The actual wall movement is less than the values predicted by both models. This behavior is likely the result of the combination of conservative modulus values for the soils, and conservative estimates of building surcharges used in our models.

The authors note that overall the wall movements for the entire site are less than predicted, even in sections where there are no building surcharges.

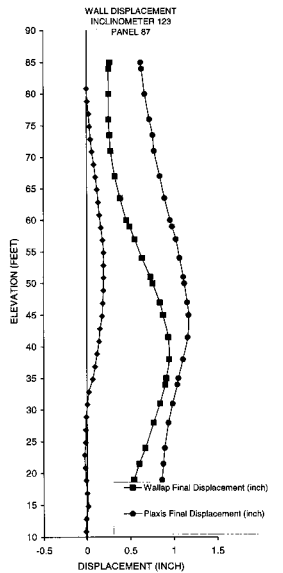


Figure 1: Modeled and Measured Wall Displacement Data

## SUMMARY

Major building foundations in urban areas with high groundwater tables can be economically constructed using permanent concrete diaphragm walls. Temporary excavation support can be accomplished using drilled and grouted anchors when the lateral right of way is available, and with internal cross lots and corner struts when anchors are not practical.

Experienced design-build teams consisting of a specialty contractor, a design firm, and, where appropriate, other subcontractors (such as an excavator) can quickly deliver foundation packages in a cooperative and productive team environment.

Design techniques that involve sophisticated soil structure interaction models combined with local data and experience give a high level of confidence for predicting wall performance on projects surrounded by other structures, where control of building movement and damage are paramount to a successful project delivery. These models need to be calibrated to empirical predictions, and other case histories of successful excavation support projects in similar ground conditions.

The use of instrumentation and the reporting of the results are important to benefit the overall knowledge base of each region where deep basements are a popular choice for building owners and developers.

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