Concrete Diaphragm Walls… One Size Does Not Fit All

Considerations for Design and Construction

By Wayne A. Chadbourne, P.E. and David W. Finocchio, P.E.

With the sustained construction trend in Boston over the past ten to fifteen years, land available for new development projects in the downtown area is valuable and scarce. Available parcels are commonly small and mired with both site and subsurface challenges. In order to achieve the pro-forma that makes these projects viable, owners are pushing their program space several levels below grade for various uses such as parking, offices, classrooms, and even for an NCAA-size regulation basketball court. In order to facilitate these deep excavations, many projects in Boston have utilized concrete diaphragm walls (diaphragm walls) for both temporary lateral earth support and permanent foundation support. The authors were recently involved with two such projects: the Manufacturer's Life Insurance Company's North American Headquarters (Manulife) and the Emerson College Piano Row Residence Hall (Piano Row). Both utilized diaphragm wall construction techniques, but for different reasons. This article highlights differences in some of the key design and construction issues, and demonstrates why "one-size" diaphragm wall does not fit all projects.

Site Development

Manulife

In the late 1990s, Manulife decided to relocate their North American headquarters from Toronto, Ontario to South Boston. One of the metrics for site selection was the requirement to provide on-site parking for the Manulife employees, as well as the other retail and commercial tenants. Because of the physical site constraints, three levels of below-grade space was necessary to satisfy the on-site parking requirements for the new development (160 vehicle capacity). The below-grade portion of the development, which occupies a footprint area of approximately 37,000 square feet, extends about 35 feet below grade and 25 feet below area groundwater levels. The rest of the development includes a new fifteen-story building providing a total of approximately 470,000 square feet of office and retail space, and a public transitway station that will service the new building and surrounding area.

Piano Row

In recent years, Emerson College set out to consolidate their facilities into a centralized campus. In pursuit of this goal, they bought a small, abandoned lot adjacent to their main campus. The abandoned lot had previously been sought by developers for construction of condominium, hotel or office projects. However, with these types of developments, the city requires prospective developers to provide on-site parking. The relatively short parcel frontage (approximately 100 feet) would not allow space for underground parking access and still leave room for a building façade. Emerson College was able to capitalize on development of this site with its proposal to construct a residence hall that did not require a parking component.

The Piano Row residence hall provides about 600 beds, a regulation-size NCAA basketball facility, a campus center and an outdoor terrace. The two-story basketball court is located about 40 feet below grade, and the campus center occupies the two below-grade floors above the court, as well as portions of the ground and second floors. The structure is approximately 15,000 square feet in plan area and has fourteen levels of above-grade space and three levels of below-grade space, requiring excavation of approximately 50 feet below the current street grade. The footprint of the below-grade structure extends to the adjacent property lines.

Rendering of finished below-grade space for Piano Row (courtesy of The Stubbins Associates)

Site and Subsurface Conditions

Due to the siting of the Manulife building, the closest structure that abutted the excavation was a tunnel located 55 feet away from the proposed footprint. The tunnel was held down using anchors grouted in the underlying bedrock.

The Piano Row site is bordered by existing buildings on three sides. These buildings contained one below-grade basement level and are supported on shallow spread footings bearing above the bottom of the proposed bottom of excavation.

Typical subsurface conditions at both sites are illustrated in *Figure 1*. The depth to bedrock was similar at both sites (115 to 135 feet below grade), however the soil conditions varied considerably. A thick, compressible deposit of marine clay was present at the Manulife site, while the marine deposit at the Piano Row site consisted of stiffer interbedded layers of clay, silt and sand. Another notable difference was the presence of a relatively thick layer (up to 40 feet) of glacial till at the Piano Row site. The static groundwater level at both sites was encountered between 10 and 20 feet below site grades.

Design Considerations

Several factors were considered by the respective design teams in order to determine the most economically and technically feasible system for creating the below-grade portions of the developments. Major design and construction factors include foundation support for the building, protecting/support of adjacent structures, finished use of below grade space and groundwater control/waterproofing of the finished below grade space.

Diaphragm walls were selected to construct the below-grade portions of both the Manulife and Piano Row projects. The requirements for protecting adjacent structures (i.e., providing adequate system stiffness), providing groundwater control and the beneficial economics of finished below-grade wall treatment were the major drivers in selection of this type of system. In the case of the Piano Row site, the necessity for deep foundation support was also a major consideration in the selection of the diaphragm wall.

Manulife

Goals for the Manulife project included maximizing the overall usage of the site while providing the required parking capacity to support the facility demand, and protecting adjacent structures on two sides of the building footprint, in particular the tunnel structure which could tolerate no more than 1/16-inch vertical movement. In order to facilitate construction of the below-grade parking area, a diaphragm wall was specified to protect the adjacent tunnel structure and several large diameter, soil-supported utility lines.

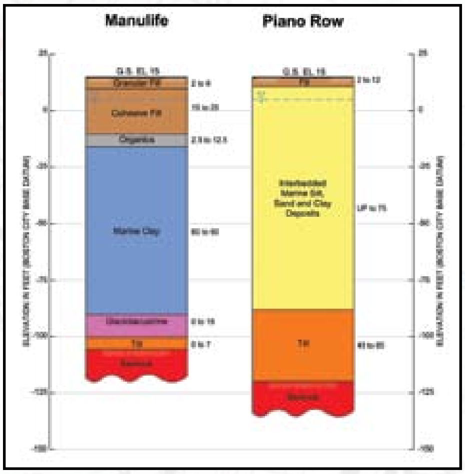

Figure 1: Generalized subsurface profiles

Due to the configuration of the building and the fact that the edges of the building footprint were set back away from the site property lines, the diaphragm wall was primarily designed to provide: 1) temporary excavation support to construct the below-grade space; and 2) a permanent groundwater cutoff wall on all sides of the excavation. The wall was designed to extend into the marine clay deposit, approximately 15 to 20 feet below the bottom of the excavation, and 60 feet above the top of bedrock. The wall was not designed to support permanent axial building loads. A 60 to 72 inch thick reinforced concrete mat foundation constructed at the base of the excavation was selected to provide permanent foundation support for the building. This system was selected primarily due to a combination of the relatively stiff nature of the clay at excavation bearing level, the static groundwater levels at the site and the relatively "light" design axial compression loads. Typical interior column loads range from 500 to 2,000 kips. Membrane waterproofing was specified beneath the mat, and the mat was designed to resist the resulting hydrostatic uplift pressures. The combination of the diaphragm walls and the waterproofed mat foundation provide an essentially water-tight space for construction of the below-grade parking garage.

Below-grade construction was not allowed within a transitway easement located adjacent to the southern limit of the below-grade space. The above-grade portion of the building extended into the easement and was supported on deep, end-bearing shafts drilled into bedrock. A flexible construction joint was incorporated into the structural design to mitigate minor differential movements that are expected to occur between the northern and southern portions of the building.

Schematic drawings depicting the diaphragm wall and bracing geometry for both projects are shown in *Figure 2*.

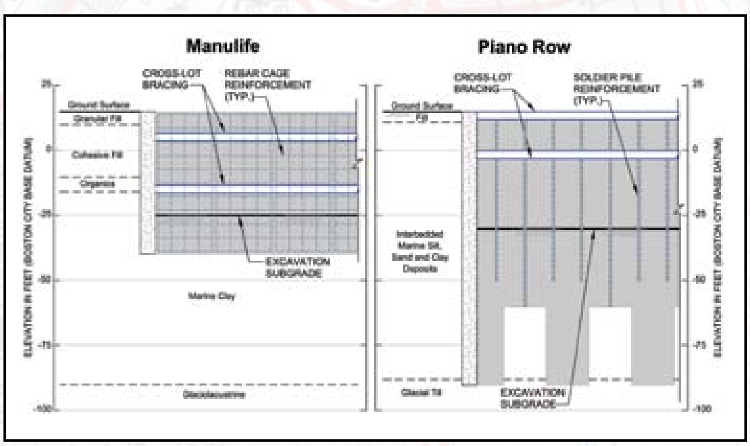

Figure 2: Diaphragm wall system schematics

Piano Row

Goals for the Piano Row project included maximizing the size and quality of interior space, protecting adjacent structures on three sides, and designing the below-grade space with the understanding of the constraints of the site. The project had to meet the challenge of bringing heavy below-grade construction to a site that is roughly the size of two residential house lots (about 15,000 square feet) that only has access on two sides. In order to facilitate underground construction on this restricted site, a diaphragm wall was specified to support and protect the adjacent structures, Boylston Street and several large diameter utilities as the excavation within the site proceeded.

Manulife project during staged excavation and mat foundation construction

The diaphragm wall was designed to carry most of the vertical structural load of the building due to the location of a full size, column-free NCAA regulation basketball court on the lowest two levels of the building. In addition to being the basement wall, the diaphragm wall system was designed to control moisture in the below-grade area to avoid damage to the wood court surface. A relatively thin composite system was applied to the interior face of the diaphragm wall to mitigate post-construction leakage through the wall. The project includes long-span structural transfers to facilitate an open (column free) space for the basketball court at the lowest below-grade level. These transfers were accomplished by trusses spanning between the perimeter below-grade walls. Typical exterior wall loads range from 35 to 75 kips per foot. The lowest level slab was designed as a pressure-relieved (underdrain provided), 8-inch thick structural slab. Reinforced concrete grade beams were installed beneath the lowest level slab to provide permanent lateral support of the foundation walls. Eight load bearing elements (LBEs) were installed at interior column support locations and were constructed utilizing the same equipment mobilized to install the diaphragm wall. Typical interior column load range from 2,000 to 3,000 kips.

Construction Considerations

Manulife

Due to need for a stiff excavation support wall and a permanent groundwater cutoff, the diaphragm wall was selected to construct the below-grade portion of the development. Use of a diaphragm wall system was more attractive due to the fact that the diaphragm wall was also used as the finished interior wall for the garage space.

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A 30-inch thick diaphragm wall was required to provide the necessary stiffness to support the excavation and to control movements of the adjacent tunnel and utility structures. The wall alignment was pre-trenched through the fill soils prior to wall installation to remove below-grade obstructions. Concrete guide walls were constructed to facilitate horizontal control of the wall construction within verticality tolerances. The wall was installed using bentonite drilling slurry and was constructed in panels typically 25 feet long. Steel rebar cages were assembled on-site and installed to reinforce each panel. Two levels of cross-lot and corner bracing provided lateral support of the diaphragm wall during excavation.

In order to control lateral wall movements and maintain the basal stability of the excavation, the contractor was required to excavate and construct the mat foundation in six separate stages. The contractor was not allowed to begin excavation for the next stage until at least 72 hours after the concrete pour from the previous section was completed.

A post-construction grouting program was implemented to seal joints in the diaphragm wall.

Diaphragm wall bracing installation at the Piano Row site

Piano Row

In order to maximize use of the small site, the building footprint covers the entire area and is constructed up to the face of the existing buildings. Due to site constraints and the need for a relatively stiff foundation wall, the diaphragm wall was constructed using a Soldier Pile Tremie Concrete (SPTC) construction instead of the typical steel rebar reinforcing. This steel could be delivered to the site and installed without having to assemble the rebar cages on the site, thus saving time and much needed space.

Temporary excavation support for this 35- to 50-foot deep excavation was provided by 24 to 36-inch thick walls that extend a minimum of 15 feet below the bottom of the excavation. Alternating sections of the wall were extended approximately 10 to 15 feet into the underlying glacial till deposit to provide permanent support of structural building loads. Panel excavation depths ranged from about 65 to 100 feet. The diaphragm wall also served as the permanent foundation wall for the below-grade space. Two levels of cross-lot and corner bracing provided lateral support of the diaphragm wall during excavation.

Diaphragm Wall Performance

For each project, performance of the diaphragm walls was evaluated using data gathered in the geotechnical instrumentation programs conducted prior to, during and after construction. Survey reference points were installed on adjacent buildings, streets and utility structures. Settlement was monitored during construction using the survey reference points. Lateral soil and wall measurements were made using inclinometers imbedded in the walls. These survey and inclinometer data were used to quantify settlements behind the support walls.

Figure 3 presents a summary of performance data collected for a number of recent diaphragm wall excavations in Boston. Normalized vertical ground movements are plotted versus normalized distance from the wall. As indicated on this figure, ground movements are typically manifested by ground settlement and lateral soil displacements (toward the excavation) immediately outside of the excavation. Movements tend to be greatest immediately adjacent to the excavation, and diminish with distance away. The lateral extent of the affected soil mass (i.e., areas where measurable settlement is observed) is usually limited to a horizontal distance away from the excavation equal to about twice the depth of excavation. Structures supported above or within this area can experience settlement and/or horizontal strain as a result of the ground movement and therefore should be monitored during construction using geotechnical instrumentation.

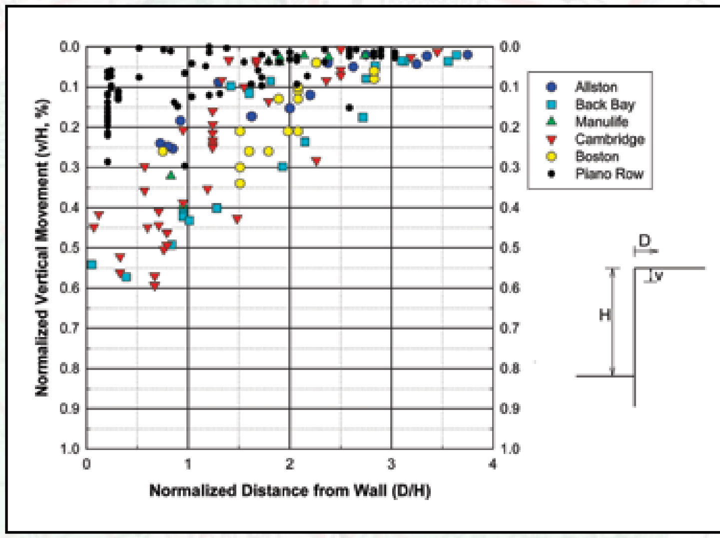

Figure 3: Normalized vertical movement vs. normalized distance from wall

Summary and Conclusions

Urban space constraints present significant challenges for owners who need to develop new facilities adjacent to existing structures. Each alternative building system must be evaluated based on its architecture, engineering and constructability merits. The path to final design typically requires concurrent resolution of political, technical, scheduling and economic issues.

The two projects described in this article depict the "bookends" of diaphragm wall use for building development. In both cases, the use of walls resulted in a technically appropriate and cost-effective solution for excavation and building support, yet for very different reasons. *Table 1* highlights how the two project teams addressed key design and construction issues. Some of the key issues considered include use of the finished below-grade space, protection of adjacent structures, waterproofing/groundwater control, structural foundation support and construction techniques.

The information summarized herein shows how the use of a diaphragm wall system requires early comprehensive planning with the entire project team in order to create functional and cost effective below-grade space.

The Manulife Headquarters building opened in late 2004 and Emerson's Piano Row Residence Hall opened in September 2006.

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Table 1 - Project Comparison.

Consideration	Manulife	Piano Row
Site Development	• 15-story office/retail space • 35 ft excavation • Below-grade parking • 37,000 sf footprint	• 14-story residential/recreation • 35 to 50 ft excavation • Below-grade basketball court • 15,000 sf footprint
Site and Subsurface Conditions	• Adjacent tunnel and utilities on two sides • Relatively open construction access • Relatively soft ground conditions	• Footing supported buildings on two sides • Utilities and subway on one side • Restricted construction access • Relatively stiff ground conditions
Design Considerations	• Protection of adjacent tunnel • Structural mat foundation • Below-mat membrane waterproof with permanent groundwater cut-off wall • Diaphragm wall from permanent lateral support • Diaphragm wall terminated 15 to 20 ft below bottom of excavation • Interior column loads 500 to 2000 kips	• Protection/support of adjacent structures and utilities • Structural Slab • Pressure relieved slab (under drained) with below slab membrane waterproofing • Composite drainage system applied to surface of wall • Finished wall sandwiched with composite drainage system • Below slab grade beams • Diaphragm wall for permanent lateral support and axial structural foundation support • Diaphragm wall terminated 45 to 80 ft below bottom of excavation • Interior column loads 2000 to 3000 kips • Wall loads 35 to 75 kips per linear foot
Construction Considerations	• Steel cages utilized to reinforce diaphragm walls • Excavation and mat foundation construction performed in six separate stages	• Steel beams utilized for SPTC wall construction • One excavation stage for slab construction • Concrete diaphragm wall construction equipment utilized for construction of interior LBEs • Alternating panels extended into the glacial till to provide support of building wall loads
Wall Performance	• Satisfactory Performance	• Satisfactory Performance

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Manulife:

Manufacturer's Life Insurance Co.	Owner
Skidmore, Owings & Merrill LLP	Architect & Structural Engineer
Clark/Suffolk, a Joint Venture	General Contractor
J. Cashman Construction	Earthwork Subcontractor
Nicholson Construction Company	Concrete Diaphragm Wall Subcontractor

Piano Row:

Emerson College	Owner
The Stubbins Associates, Inc.	Architect
LeMessurier Consultants	Structural Engineer
GBH Macomber Company	General Contractor
A.A. Will Corporation	Earthwork Subcontractor
East Coast Slurry	Concrete Diaphragm Wall Subcontractor

Wayne A. Chadbourne, P.E., a Senior Engineer with Haley & Aldrich, has 12 years of experience including foundation design for low- and high-rise structures, bridges and marine/waterfront structures using drilled shaft, mat, spread footing, grouted rock anchors and various types of pile foundations. Mr. Chadbourne also has experience in development of below-grade space, underpinning and lateral support systems for deep excavations.

David W. Finocchio, P.E., a Senior Engineer with Haley & Aldrich, has 12 years of experience including shallow and deep foundation design, excavation support, excavated soil management, and construction dewatering. Mr. Finocchio also has experience that includes underpinning, design of concrete diaphragm walls and evaluating performance of various mat and pile supported structures.