Geologic Influences on Major Building Foundations in Boston

A summary of all of the major building foundations, with notes on how their construction added to understanding Boston's geology.

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The influence of geology on building in Boston goes hand in hand with the building technologies of the day and the development of the city itself. The following review of building development incorporates information from E.G. Johnson (in Woodhouse & Barosh, 1991), along with information on the subsequent building additions of the past twenty-five years.

In the early Colonial days within the original Shawmut Peninsula, Bostonians built utilitarian structures, often of wood, with simple wood or stone foundations. Most neighborhoods were eventually leveled by major fires and only Paul Revere's house (dating from 1677) remains as an example from that era. As Boston prospered during the 1700s, more durable buildings were raised that used brick or stone. These structures include several surviving large public buildings such as the Old State House (1712), the Old South Meeting House (1729), King's Chapel (1749) and many edifices on Beacon Hill, including Bulfinch's gold-domed State House (1795). These buildings were all constructed on solid ground and probably supported on footings of granite largely supplied from quarries in Quincy. Construction also pushed toward the waterfront where Faneuil Hall (1740) and Quincy Market (1824) had to be supported on wood piles driven through the fill and underlying organic mud to firm end bearing. The original brick Custom House (1810) was constructed on Custom House Street — a small street running northeast that connects Batterymarch and India streets, just southwest of the Central Wharf — on footings and was replaced by the now existing Custom House in 1847, with its tower added between 1913 and 1915. The venerable old Custom House thus became Boston's first skyscraper — standing 151 meters (496 feet) high, with thirty-six stories (thirty-two floors in the tower alone) — even though the city had a 38 meter (125 foot) height restriction, which was waived since the Custom House was a federal government building. The new Custom House of 1847 used three thousand piles driven to the outwash or the till, which occurs at a depth of 18 to 27 meters (60 to 90 feet). It has been variously reported that the piles were driven to bedrock (Seasholes, 2003), but doing so would have been unlikely since the piles would have had to penetrate through 4.5 to 7.6 meters (15 to 25 feet) of dense outwash and till, something that would have not been possible for the pile-driving equipment of the day. Bedrock in the area is found at an elevation of –30 meters (–100 feet) MSL. The *1850 Boston Almanac* does not confirm that piles were driven to bedrock for the original new Custom House.

During the second half of the nineteenth century, Boston was ready for change and expansion since it reached the outer limit of its buildable land. Industrialization and the building of railroads greatly improved construction capabilities. The 182 hectares (450 acres) of marsh land that was once Back Bay were filled in with sand and gravel brought in by rail from Needham to the west and Dedham to the southwest (Newman & Holton, 2006). The area was laid out in a grid of streets. Fashionable brick town houses lined these streets as well as several cultural institutions (Seasholes, 2003), including the original Museum of Fine Arts (now moved to Huntington Avenue), the Museum of Natural History (currently extant on Berkeley Street between Boylston and Newbury streets — now being renovated), the original Massachusetts Institute of Technology (MIT moved to Memorial Drive in Cambridge in 1916), the Arlington Street Church, New Old South Church (now called the Old South Church), Horticultural Hall (closed), Symphony Hall and the original Boston Public Library (demolished in 1899, after completion of the new Boston Public Library, which was built between 1888 and 1895). Also present are the beautiful Trinity Church that faces the library at Copley Square and the Christian Science Mother Church and Center, which lie farther to the west. For all of these structures, the standard foundation practice was support by untreated wood piles, typically 7.5 to 12 meter (25 to 40 foot) long trees, driven to bearing in the outwash sand and gravel layer or crust of the thick marine clay deposit (Aldrich & Lambrechts, 1986) that underlie the fill and organic deposits.

Before the 1880s, wood piles were driven by dropping a heavy weight on them that was lifted between guides using animal or manpower. Later, steam power was used to raise the weight. The Arlington Street Church used 999 piles and the Trinity Church used 4,500 (2,800 under the four columns of the central tower alone) driven into the upper outwash. A similar number (more than 4,000) of wood piles was used for the new Boston Public Library in the 1880s. These piles have generally performed well, except where the pile cutoffs have been exposed to drying and decay. The Old South Church had pile failure due to poor underlying material used to support the wood piles (according to information provided by the church), and again later in 1913 through 1914 that was caused by subway construction in a deep excavation beneath Boylston Street. These problems caused the original tower to lean over 41 centimeters (16 inches) off vertical.

Relatively little new building construction took place in the early twentieth century, except for the tower added to the Custom House. Several structures were built in the 1920s and 1930s in the Back Bay, notably the John Hancock Berkeley Building, the Liberty Mutual Building and the New England Mutual Building. However, heights were generally limited due to the thick marine clay and the onset of the Great Depression. The first very tall building in Back Bay was the John Hancock Clarendon Building in 1946, which used deep steel H-piles to penetrate through the clay to bear on till and bedrock.

Boston's building renaissance began in the Back Bay in 1959 with major developments that included the first break into the skyline with the Prudential Center, a fifty-two-story office tower, with an adjacent twenty-nine-story hotel. These, and most other, tall buildings in the Back Bay built in the past fifty years have used deep foundations to support building loads below the clay on till or bedrock. This building boom took off in earnest in the 1960s, and is still continuing today. A list of buildings constructed from 1959 to the present, with available information on date of construction and foundation characteristics, is shown in Table 5-1, and the locations of ones built from 1960 to the present are shown in Figures 5-1, 5-2 & 5-3. At times, Boston's history lost out to site clearing. For example, the razing of the infamous Scollay Square and the old West End for the development of Government Center. The dramatic change in the Boston skyline during this period is easily seen in aerial views (see Figures 5-4 & 5-5). Centers of construction sprang up in the city, with each involving a need for new types of foundations and excavation support systems to accommodate the different geologies that underlay them. Because of the large size and loads of these new buildings, geologists and design engineers knew that they no longer could rely on wood pile foundations or on granite block footings, thus creating plenty of opportunity for innovation in the new science of geotechnical engineering and geo-construction.

As Boston developed, severe space restrictions added complexities to foundation design and construction in addition to the complicated geologic conditions. Where adjacent historic properties required protection during deep excavations (such as at 60 State Street), tied-back slurry walls were used. At 53 State Street, the granite facade of the existing Boston Stock Exchange Building was temporarily supported while a new glass-enclosed high-rise was built immediately behind it. Similarly, temporary facade support was undertaken at the 101 Arch Street and 125 Summer Street projects. Deeper excavations below buildings now are commonly called for to provide space for badly needed parking. Recent examples (Becker, 1991) include International Place (five levels), Rowes Wharf (five levels), 125 Summer Street (five levels), 75 State Street (five levels) and the garage below the park at Post Office Square provides seven levels for parking (see Figure 5-1). The latter utilized the "up-down" construction technique. Finally, the Central Artery/Tunnel Project required the application of recently developed equipment and techniques to make possible the installation of high-capacity foundation units and slurry walls below existing structures in low headroom conditions.

The number of new buildings constructed in downtown Boston slowed because of a recession in Boston's economy in the 1990s and again in the 2000s. Most construction in this period occurred in the South Station and Seaport area of South Boston and some farther out. Since 2012, tall building construction has resumed in the inner city with significant structures at Millennium Place and in Chinatown.

Back Bay: Public Garden to Copley Square. Copley Square in the Back Bay (which included the Prudential Center) was the site of Boston's first great development outside the downtown area and the home to many historic buildings in the city. These old buildings include the venerable nineteenth century Trinity Church (1876), New Old South Church (1875) and the Boston Public Library (built from 1888 to 1895). The library was expanded in 1972 with a four-story addition that was supported by a thick concrete mat on the stiff clay and upper outwash sand. Most if not all of the more than hundred-year-old buildings are supported on untreated wood piles, some of which have been affected by construction dewatering or a lowering of groundwater levels due to various causes.

The major development in the area, which occurred between 1968 and 1982, had begun with the sixty-story John Hancock Tower — the tallest structure in Boston and totally wrapped with reflective glass. The tower bears on a 2.6 meter (8.5 foot) thick concrete mat that is supported on 3,000 steel H-piles that extend deep into till and argillite. Bostonians remember all too well the problems with I.M. Pei's designed building that began with large movements of the excavation support system that caused substantial damage to adjacent streets, utilities and buildings. Later, during construction, the large pane double-glazed glass windows started to crack, break and fall to the pavement below. Plywood quickly replaced glass. The problem was corrected by changing the glass to a thicker single-glazed panel. It was learned that trace elements in the original double-glazed

TABLE 5-1.
Major Buildings Constructed in Boston Since 1960 & Their Type of Foundation

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Downtown Boston
1	First National Bank, 100 Federal Street	1971	C	IV-A-1 or VI-A-1	30-story office tower; footings/mat on glaciomarine or moraine deposits
2	Shawmut Bank, 1 Federal Street	1975	C	IV-A-1 or VI-A-1	30-story office tower; footings/mat on glaciomarine or moraine deposits
3	State Street Bank, 225 Franklin Street	1966	C	IV-A-1 or VI-A-1	30-story office tower; footings/mat on glaciomarine or moraine deposits
4	Office Building, 265 Franklin Street	1983	C	IV-A-1 or VI-A-1	20-story office tower; footings on glaciomarine or moraine deposits
5	One Post Office Square	1979	B	VI-3	38-story office tower & parking structure; PIFs to glacial till
6	Office Building, 260 Franklin Street	1983	C	VI-A-2	23-story office tower; spread footings on till at depth 7.5 m (25 ft)
7	Office Building, South Milk Street	1980	B	IV-A-1	21-story office tower; footings on stiff clay
8	The Devonshire, One Devonshire Place	1980	C	VI-A-2	40-story apartment & office tower; combined footings on moraine deposits
9	Boston Co. Bldg., One Boston Place	1968	C	VI-A-2 & VII-4	41-story office tower; core on mat on moraine gravel; heavy corner loads on belled piers in argillite at 24 m (80 ft)
10	Office Building, One Beacon Street	1970	C	VI-A-2	40 story office tower; concrete mat on moraine deposits
11	Office Building, One Washington Mall	1968	B	IV-A-1	12 -story office building; spread footings at depth 6 m (20 ft)
12	Office Building, 28 State Street	1965	B	VI-A-1	40-story office tower; concrete mat bearing at depth 10.5 m (35 ft)
13	Office Building, 60 State Street	1976	C	VI-2 & VI-A-4	38-story office tower; 3-level basement; concrete mat on glacial till; belled caissons below plaza level
14	Office Building, 53 State Street	1982	B/C	VI-2, VI-3 & VI-1	40-story office tower; core on deep concrete mat on till; perimeter on concrete-filled pipe piles to till/bedrock
15	Public Parking Garage Dock Square	1978	B	VI-3	7-level parking structure; pre-stressed concrete piles to glacial till
16	Marketplace Center, State Street	1983	B	VI-3	16-story office building; pre-stressed concrete piles to till
17a	Lafayette Place, Washington Street, hotel	1980	B	VI-3	20-story hotel; concrete-filled pipe piles to till; depth 17 m (55 ft)
17b	Lafayette Place, Washington Street, office	1984	B	IV-A-1	3-story retail; 3 levels parking below; spread footings on sand
18	Office Building, 75 State Street	1986	B	VII-2	31-story office tower, 6 levels below; belled & straight-shaft caissons in argillite; slurry wall "up-down" construction
19	International Place, High Street	1985	C	VI-A-2	11 to 46 story office towers; 5 levels below; concrete mat & footings on till
20	33 Arch Street	2004	C	VII-2	33 story residence; 2.4-3.7 m (8-12 ft) diameter shafts drilled 3-10.6 m (10-35 ft) into argillite at depth 21-38 m (70-125 ft)
21	One Lincoln Street	2003		VII-2	36-story office tower, up-down construction with 5 levels; 17-20 m (55-65 ft) deep excavation; slurry wall cutoff & foundation wall keyed into till; interior column footings on till
22	W Boston Hotel & Residences, 100 Stuart St	2007/9	A	VI-A-2	25-story hotel; mat foundation on stratified sand, clay & silt
23	125 High Street	1991	B	VI-1	30-story office building on spread footings on till
					Waterfront
24	Long Wharf Hotel, Atlantic Avenue	1979	B	VI-3	9-story hotel; pre-stressed concrete piles to till
25	Harbor Towers & Garage, Atlantic Avenue	1969	B	VI-3	Two 40-story apartment towers & 6-story garage; concrete-filled pipe piles to depth 18-27 m (60-90 ft)
26	Rowes Wharf Development, Atlantic Avenue	1985	B	VI-4	15-story office/hotel, 5 levels below; belled caissons in till; slurry wall, "up-down construction"
27	Office Building, 745 Atlantic Avenue	1987	B	IV-A-1	10-story office, 3 levels below; concrete mat on sand
28	U.S. Coast Guard, EMS Bldg., Atlantic Ave.	1981	B	III-1	3-story maintenance facility; new structural mat over existing wood piles, plus additional pre-stressed concrete piles
29	Russia Wharf	2010	A	IV-2, VI-2 & VI-3	Hotel, condos, offices; load testing of existing wood piles on clay & till with ground freezing; mini-piles bearing on till; underlain by new Silver Line Tunnel
30	Intercontinental Hotel, 510 Atlantic Ave.	2006	A	VI-3 & VII-2	22-story hotel/condo wrapped around CA/T vent shaft; 2-concrete towers; perimeter slurry wall in till; drilled caissons to argillite; wharf on pre-augered, pre-stressed/pre-cast concrete piles bearing on till
					Copley Square
31	Exeter Towers, Exeter & Newbury Streets	1980	A	III-2	6-story apartment building; PIFs bearing in outwash sand
32	One Exeter Place, Exeter & Boylston Sts.	1983	A	III-2	13-story office building; pre-stressed concrete piles to depth 44 m (140 ft)
33	Boston Public Library Addition, Boylston St.	1972	A & B	IV-A-1	4-story library addition; mat foundation bearing on stiff clay & sand

Note: Key # corresponds to location noted in either Figure 5-1, 5-2 or 5-3.

(Table continued on next page)

TABLE 5-1.
Major Buildings Constructed in Boston Since 1960 & Their Type of Foundation (cont'd)

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Copley Square (con't.)
	Copley Place Project				All buildings founded on pre-stressed concrete piles driven to till or argillite at depth 30-50 m (100-165 ft)
34a	Copley Place Project, Westin Hotel	1980	A	VI-3 or VII-1	38-story hotel
34b	Copley Place Project, Central Hotel	1981	A	VI-3 or VII-1	Up to 15-story retail, office & parking
34c	Copley Place Project, Marriott Hotel	1982	A	VI-3 or VII-1	35-story hotel
35a	John Hancock Tower, St. James & Clarendon	1969	A	VI-III or VII-1	60-story office tower; steel H-piles driven to till or argillite
35b	John Hancock Parking Garage	1968	A	VII-2	8-story parking garage; H-piles & drilled-in-caissons into argillite; built on air rights above Massachusetts Turnpike Extension
36	The Clarendon, 400 Stuart Street	2006	A	VII-2	32-story offices & residences; 3 levels below grade with lowest level on mat design to resist hydrostatic uplift; foundations consist of LBEs in slurry wall shafts for internal columns & drilled shaft /caissons in argilllite
37	Mandarin-Oriental Hotel, Boylston St.	2003-8	A	V-2 & VII-1	Two 14-story towers on 220 ton high-capacity mini-piles permanently cased to argillite & doweled 0.68 m (2.3 ft) thick mat at 7.6 m (25 ft) bearing on outwash
					Prudential Center
38a	Prudential Center, Office Tower	1959	A	VII-2	52-story office tower; drilled-in-caissons, bearing in argillite at depth 66 m (200 ft)
38b	Prudential Center, Sheraton Boston Hotel	1962	A	VI-3	29-story hotel; 0.4 m (16-in.) diameter concrete-filled pipe piles to till at 45-60 m (150-200 ft)
38c	Prudential Center, Southeast Tower	1962	A	VI-3	29-story hotel; 0.4 m (16-in.) diameter concrete-filled pipe piles to till at 45-60 m (150-200 ft)
38d	Prudential Center, Apartment #5	1962	A	VI-3	26-story apartment building/hotel; 0.4 m (16-in.) diameter concrete-filled pipe piles to till at 45-60 m (150-200 ft)
38e	Prudential Center, Apartments #1 & #3	1963	A	VII-2	26-story apartment buildings; drilled-in-caissons to argillite at depth 55 m (180 ft)
38f	Prudential Center, Lord & Taylor	1966	A	VI-3	5-story retail store; concrete-filled pipe piles to depth 42 m (140 ft)
38g	Prudential Center, Sak's Fifth Avenue	1970	A	III-2	5-story retail store; PIFs & wood piles bearing in outwash sand
39	Colonnade Hotel, Huntington Avenue	1971	A	III-2	12-story hotel; PIFs bearing in outwash sand
40	Hilton Hotel, Dalton Street	1981	A	VI-3	20-story hotel & garage; pre-stressed concrete piles & PIFs
41	Hynes Auditorium, Boylston Street	1960	A	VI-3	Two-level municipal auditorium, basement; concrete-filled pipe piles to till or rock at depth 60 m (200 ft)
42	Hynes Convention Center	1985	A	VII-2 (mod)	Expansion area; drilled piles into argillite (250 tons)
43	111 Huntington Avenue	2001	A	VII-2 (mod)	36-story office building; 1.2-1.8 m (4-6 ft) diameter drilled shafts into argillite at 43 m (140 ft)
					Christian Science Church Center
44	Church Park Apartments	1971	A	III-2	10-story apartment building; PIFs in outwash sand
45	Church Park Garage	1971	A	III-2	6-story parking garage; PIFs in outwash sand
46	Symphony Towers, Mass Ave & Huntington	1971	A	III-2	Two 12-story apartment buildings; PIFs in outwash sand
47a	Church Center, Sunday School Bldg.	1968	A	III-2	Five-story building; PIFs in outwash sand
47b	Church Center, Colonnade Building	1968	A	III-2	Five-story building; PIFs in outwash sand
47c	Church Center, Administration Building	1968	A	VI-3	28-story office building; concrete-filled pipe piles to depth 52 m (170 ft)
48	Greenhouse Apartments, Huntington Ave	1981	A	III-2	12-story apartment building; PIFs in outwash sand
49	Ingalls Building, 855 Boylston Street	1987	A	III-2	12-story office building; PIFs in outwash sand
					Government Center
50	One, Two & Three Center Plaza	1963	C	VI-A-2	8-story office building; footings on moraine deposits
51	McCormack State Office Building	1969	C	VI-A-2	22-story office building; footings on moraine deposits
52	Saltonstall State Office Building	1963	C	VI-A-2	16-story office building; concrete-filled pipe piles into till
53	J.F. Kennedy Office Building	1966	C	VI-A-3	25-story office building; mat foundation
54	State Services Center, Staniford Street	1970	C	VII-2	8-story office building; drilled rock-socketed caissons
55	Boston City Hall	1964	B	VI-3	6-level municipal building; concrete-filled pipe piles to till
56	U.S. Government Services Building	1985	B	VI-3	10-story office; pre-stressed concrete piles to till, portion on steel H-piles

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Boston Commons & Public Area
57a	Taj Boston Addition, Arlington Street	1980	B	III-2	18-story hotel; PIFs
57b	Taj Boston Parking Garage, Newbury St.	1980	B	IV-A-2	Friction pre-stressed concrete piles in marine deposits
58	Four Seasons Hotel, Boylston Street	1982	B	III-2	13-story hotel/condominium; 2 levels with parking under; PIFs to sand layers in marine deposits
59	State Transportation Building, Park Plaza	1981	B	IV-A-1	8-story building; concrete mat foundation at depth 10.5 m (35 ft); slurry wall around perimeter
60	Tremont-on-the-Common, Tremont St.	1963	B	VI-3	25-story apartment; concrete-filled shell piles to till
61	500 Boylston Street/222 Berkeley Street	1986/9	A	IV-A-1	25- & 6-story office buildings with 3 parking levels below; mat foundation on marine clay for larger building; spread footings & tension piles for 6-story building; 29- & 23-story buildings with 3 levels parking below; slurry wall for excavation
62	Heritage on the Garden, Boylston Street	1986	B	IV-A-1	13-story condominium, 2 & 3 levels below; concrete mat on marine deposits
63	Millennium Place I, II & III	2001	C	VI-A-2	Ritz-Carlton, 36- & 38-story hotel towers; I utilized up-down construction & LBEs; II & III on mat foundation on deformed clay & sand
64	45 Province Street	2009	C	VI-2	31-story residences; slurry wall & 1.2-m (4-ft) diameter caissons in till at depth 18-23 m (60-75 ft)
96	MP-3, Hayward Place	2012	C	VI-A-2 & VII-2	15-story residential tower on split foundation consisting of mat on overthrust deposits & 1 m (3-4 ft) diameter drilled shafts in argillite to depth 24 m (80 ft)
					South End & Chinatown
65	Bradford Towers West, Stuart Street		B	IV-1	4-,6- & 9-story housing; caissons in stiff clay
66	Bradford Towers East, Tremont Street		B	IV-A-1	5- & 7-story housing; spread footings on clay, portion on deep caissons near subway
67	Elderly Housing, Washington Street		B	IV-A-1	Concrete mat on clay
68	Tufts Health, Science, Education Bldg.	1984	B	IV-A-1	9-story medical facility; concrete mat on clay
69	Wang Laboratories, Kneeland Street	1984	A	VII-1	10-story building; pre-stressed concrete piles to till or bedrock at 38 m (125 ft)
70	Tufts New England Medical Center	1978	B	VII-1	9-story medical center; pile driven to bedrock for high column
71	Boston Common/Park-Essex, 600/660 Washington Street	2003	B		28-story residential building formerly called Park Esssex; drilled caissons supporting a 1 m (3 ft) thick mat at depth 7.6m (25 ft) below street; caissons drilled to depth 33.5 m (110 ft), 3-4.5 m (10-15 ft) rock socket into argillite
					South Station & South Boston
72	Keystone Building, 225 Congress Street	1969	C	VI-A-2	17-story office tower; footings on glacial till
73	Federal Reserve Building	1973	C	VI-A-2	35-story office tower; concrete mat on till
74	Stone & Webster Building, Summer St.	1973	B	VI-3	14-story office building; concrete-filled piles to till or rock
75	South Postal Annex Addition, Dorchester Ave.	1971	B	VII-1	6-story building; concrete-filled steel pipe piles to bearing in argillite
76	Office Building,101 Federal Street	1986	B	VII-2	32-story office building with 2 levels below; straight shaft caissons socketed in bedrock, concreted under slurry
77	Office Building, 150 Federal Street	1986	B	IV-A-1	28-story office;3 levels below; spread footings on marine deposits
78	101 Arch Street	1986	C	VI-A-4	21-story office; belled caissons in till concreted under slurry
79	Office Building, 99 Summer Street	1986	C	VI-A-2	22-story office; footings on glacial till
80	Office Building, 125 Summer Street	1987	C	VI-A-2	Special 23-story office tower with 5 levels below; LBEs (barrettes) in till & rock; slurry wall "up and down" construction
81	Office Building, 100 Summer Street	1971	C	VI-A-4	33-story office tower; belled caissons bearing in till at depth 9 m (30 ft)
82	Office Building, 175 Federal Street	1973	C	VI-A-4	14-story office tower; belled caissons bearing in till at depth 12 m(40 ft)
83	One Financial Center	1979	C	VI-A-2	46-story office tower with 2 levels below grade; concrete mat on till
					Seaport & South Boston
84	Manulife US Headquarters, 601 Congress St.	2004	A	VII-2 & IV-1	14-story tower with 12 m (40 ft) deep 2.5 levels of below grade parking; southern portion on 1.2 m (4 ft) diameter shafts drilled into several feet of bedrock; remainder 1.2-1.5 m (4-5 ft) thick concrete mat floating on marine clay with slurry wall toed into clay
86	Renaissance Boston, 606 Congress St.	2008	A	VI-1 & VII-1	22-story waterfront hotel, 18 m (60 ft) pre-augered, pre-stressed/pre-cast concrete piles driven to till & bedrock at 30.5 m (100ft).

Note: Key # corresponds to location noted in either Figure 5-1, 5-2 or 5-3.

(Table continued on next page)

TABLE 5-1.
Major Buildings Constructed in Boston Since 1960 & Their Type of Foundation (cont'd)

Key #	Building & Location	Year Built	Typical Soil Profile	Soil Unit & Foundation Type	Description
					Seaport & South Boston (cont'd)
87	Fan Pier (including office building at One Marina Park Dr., Vertex at 50 Northern Ave & 11 Fan Pier Blvd)	2010	A	IV-A-1 & IV-1	18-story office buildings located on Fan Pier. 1.2-1.8 m (5-6 ft) thick concrete mat on clay at depth of 12 m (40 ft); in area of old boat slip channel, One Marina Park Drive also used straight-shaft caissons (friction) in clay at 21 m (70 ft) = 9 m (30 ft) below mat
88	Boston Convention & Exhibition Center/ Westin Boston Waterfront Hotel, 415/ 425 Summer Street	2006 to 2009	A	VI & VII-1; VI-2 & VII-2	Convention center & adjoining 17-story Westin Boston Waterfront Hotel; Convention Center bearing on pre-cast 35.5 x 35.5 cm (14 x 14 in.) concrete piles driven to till & argillite and 1.2-2 m (4-7 ft) diameter caissons drilled to argillite for the larger loaded columns & lateral resistance; the low-rise portion of the hotel bearing on 105 ton design capacity 32.4 x 1 cm (12.75 x 0.375 inch) wall thickness concrete filled pipe piles driven to end bearing in till & argillite; high-rise section of hotel/tower supported on a series of 1-2 m (3-6 ft) diameter rock-socketed drilled caissons
89a	World Trade Center East/Seaport Center East 2 Seaport Lane/255 Seaport Blvd	2000	A	IV-A-1	16-story office with 3-level below grade garage; concrete mat on clay
89b	World Trade Center West/Seaport Center West/155 Seaport Blvd	2002	A	IV-A-1	17-story office with 3-level below grade garage; concrete mat on clay
90	Seaport Boston Hotel, 1 Seaport Lane	1996 to 2000	A	IV-A-1	14-story hotel, 17-story west office bldg., 17-story east office bldg. with 3-level garage under; buildings on mat bearing on marine clay; garage on spread footings on clay; perimeter wall sealed into top of clay as groundwater cutoff
91	Park Lane Seaport I & II, 1 Park Drive	2004 to 2006	A	IV-A-1 & VI-1	13- & 21-story residential buildings; low-rise bearing on 1.2-1.8 m (5-6 ft) thick mat on clay at depth 12 m (40 ft); high-rise on steel H-piles bearing on till at depth 33.5-36.5 m (110-120 ft).
					Charles River Park & Longfellow Place
92a	510 Emerson Place	1960	B	VI-3	15-story apartment on concrete-filled piles
92b	10 Emerson Place	1960	B	VI-3	23-story apartment on concrete-filled piles
92c	8 Whittier Place	1962	B	III-2	23-story apartment on PIFs
92d	6 Whittier Place	1962	B	III-2	15-story apartment on PIFs
92e	Amy Lowell House	1974	B	III-2	11-story apartment on PIFs
92f	Parking Garage	1973	B/C	III-4 & VI-A-3	Spread footings & pipe piles
92g	One & Two Hawthorne Place	1973	B/C	III-4 & VI-A-3	15-story apartment; spread footings & caissons
92h	One Longfellow Place	1973	C	VII-A-1	36-story apartment; spread footings on rock
92i	Four Longfellow Place	1973	C	Vi-A-3	36-story apartment; concrete-filled pipe piles
92j	South Staniford Street	1973	C	VI-A-1	10-story apartment; spread footings on soil
93a	Massachusetts General Hospital, Charles Street, Ambulatory Care Center	1980	B	VI-3	8-story medical facility; concrete-filled pipe/steel shell (composite) piles to till at depth 21 m (70 ft)
93b	Massachusetts General Hospital, Cox Bldg.	1979	B	III-2	7-story medical facility; PIFs in sand
93c	Massachusetts General Hospital, Lunder Bldg.	2010	A	VI-VII-2	14-story medical building with up-down construction, 3 levels below grade; perimeter slurry wall; interior columns on 1.2 m (4 ft) diameter drilled caissons in till & bedrock
94	Massachusetts Eye & Ear Infirmary, Charles Street	1969	B	VI-2	13-story facility; adjacent & above original 5-story wood pile supported building;150 ton PIFs in till at 24 m (80 ft) with steel cased shafts
95	Spaulding Rehabilitation Ctr, Nashua St.	1980	B	VI-3	10/6-story nursing facility; concrete-filled pipe piles to till
96	Liberty Hotel, 215 Charles Street	2007	C	VII-1	16-story hotel on pre-stressed/pre-cast concrete piles
					Huntington Avenue & Longwood Medical Center
97	541-555 Huntington Ave, Wentworth Institute	2003	A	IV-1 & IV-2	7-story residential building; western portion of site on belled caissons in yellow clay crust; eastern portion on mini-piles in clay to avoid MWRA Muddy River sewer easement
98	West Campus, Northeastern U., Bldgs A-G	2000	A	IV-4	6 buildings, 4-11 stories, with 1-1.2 m (3.5-4 ft) thick mat foundations bearing on shallow stiff clay at depths between 2 & 6 m (7-20 ft)
99	International Village, Northeastern U.	2000	A	IV-4 & III-2	3 dormitory buildings 22-24 stories with 5-story interconnected bldg.; dormitories on 1-1.2m (3.5-4 ft) thick mats bearing on stiff clay at depth of 6 m (20 ft); 5-story building on PIFs in upper outwash

Note: Key # corresponds to location noted in either Figure 5-1, 5-2 or 5-3.

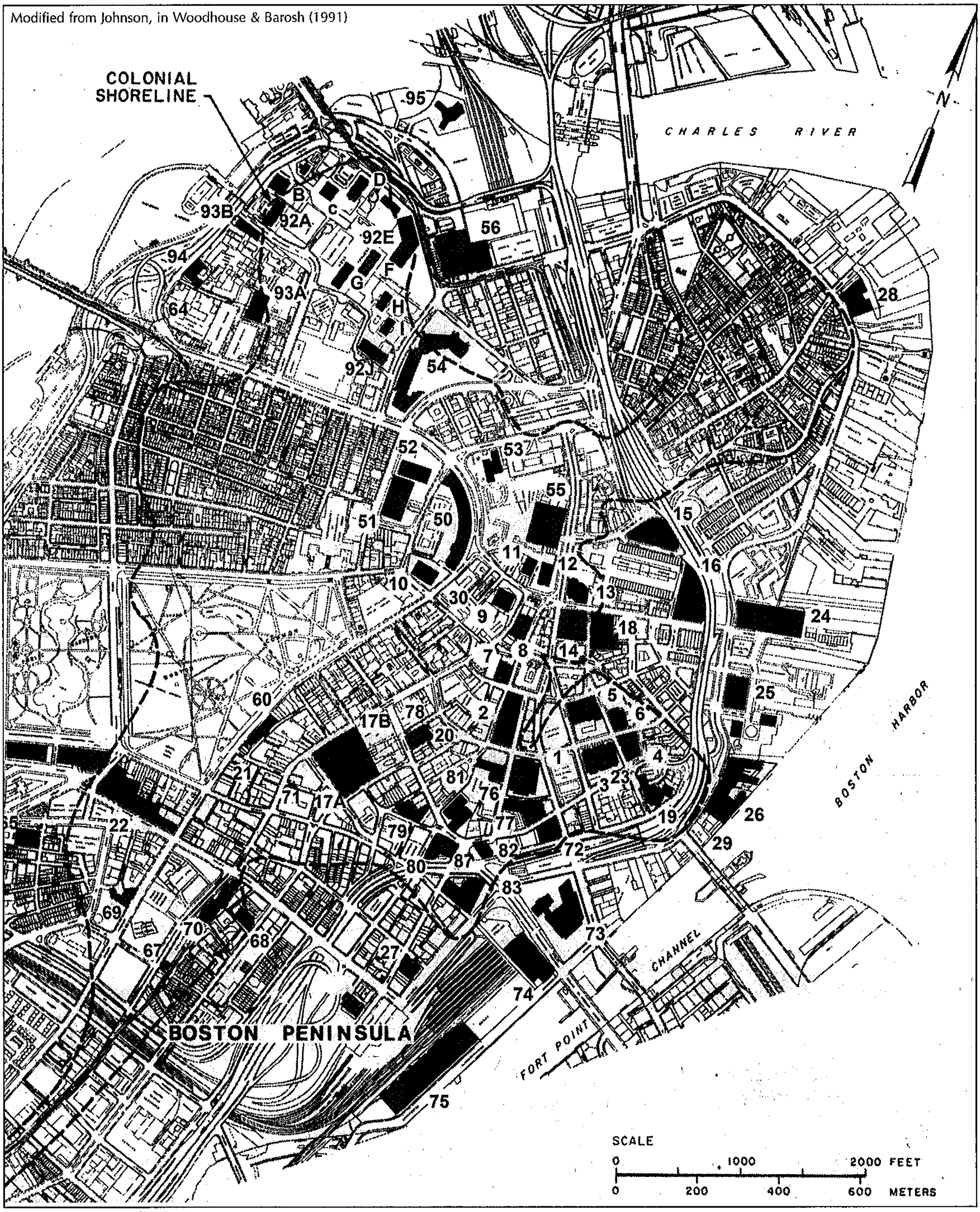


FIGURE 5-1. Map of downtown Boston showing the location of major buildings constructed since 1960.

glass were causing an inherent weakness in the windows when they experienced stress from wind load and differential thermal gradients.

The nearby John Hancock Parking Garage required the installation of 30 meter (100 foot) deep drilled-in caissons into the argillite. Some were installed within a narrow median strip

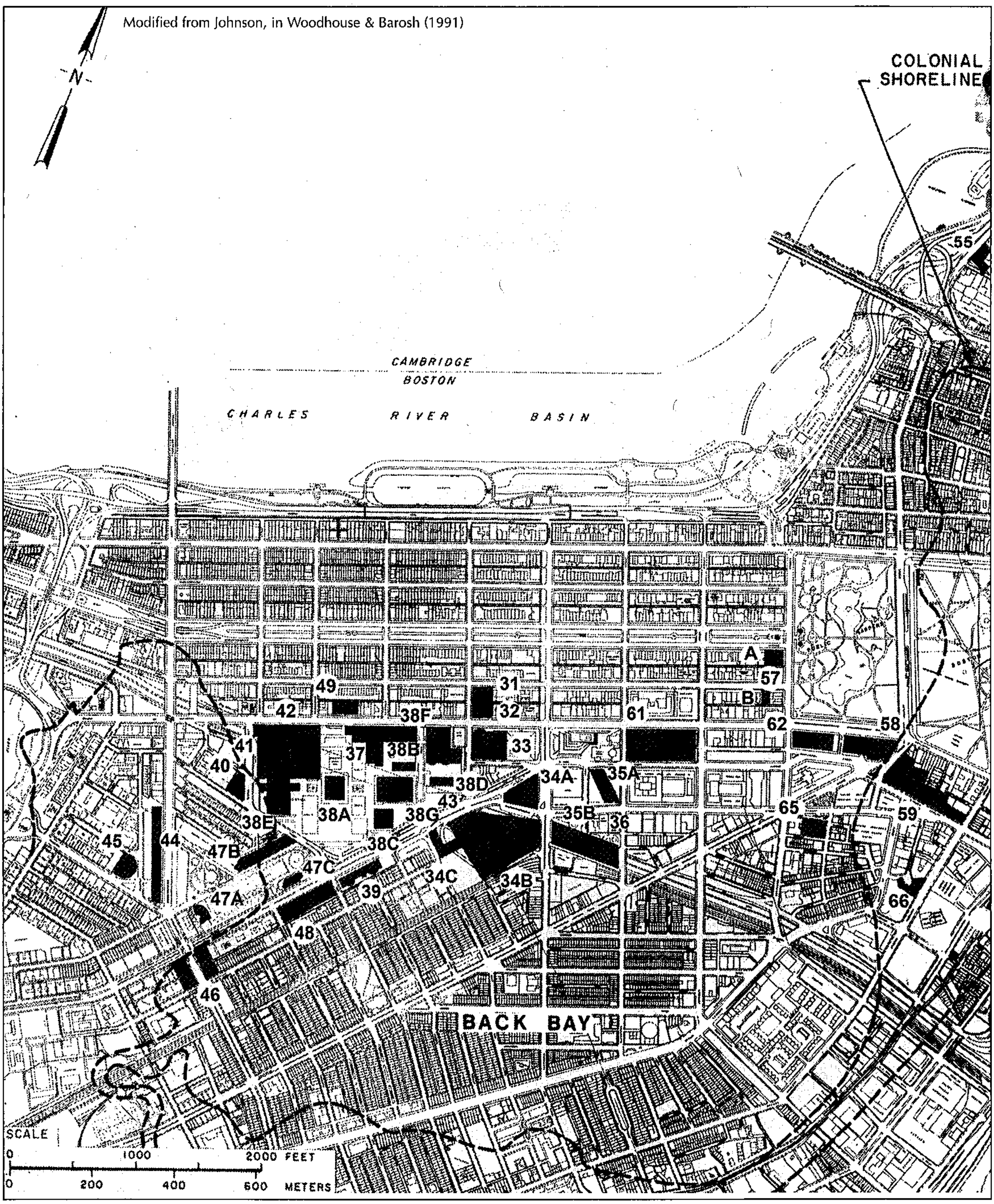


FIGURE 5-2. Map of Back Bay showing the location of major buildings constructed since 1960.

between depressed roadway sections of the Massachusetts Turnpike Extension. The Copley Place Project, built in the early 1980s on a triangular plot of land bounded by Dartmouth Street, Stuart Street and Huntington Avenue, includes two hotels (thirty-five and thirty-eight stories), plus offices and retail space. Foundations consist of pre-stressed concrete piles driven to till or bedrock at depths between 30 and 50 meters (100 and 165 feet).

Recently, the twenty-five-story Liberty Mutual Building has been constructed in 2012 at the corner of Berkeley Street and Columbus Avenue. Its foundation and structure consist of up-down construction with four levels below grade that utilize slurry walls and internal slurry panels called load-bearing elements (LBEs). Surficial materials consist of 6 meters (20 feet) of fill, a 6 meter (20 foot) layer of organic silt and a 23 meter (75 foot) layer of typical marine clay having depths of 12 to 35 meters (40 to 115 feet), below which the bedrock was found. Many old wood piles and Gow caissons hindered excavation operations. Also using a similar type of foundation is the Clarendon, a thirty-two-story office and residential tower that was constructed from 2006 to 2008 at the corner of Stuart and Clarendon streets south of the John Hancock Tower. The building consists of three levels below grade that use slurry wall construction, with the lowest level on a mat design that resists hydrostatic uplift. Foundations consist of LBEs in the slurry wall shafts for the internal columns and drilled shafts/ caissons into the argillite.

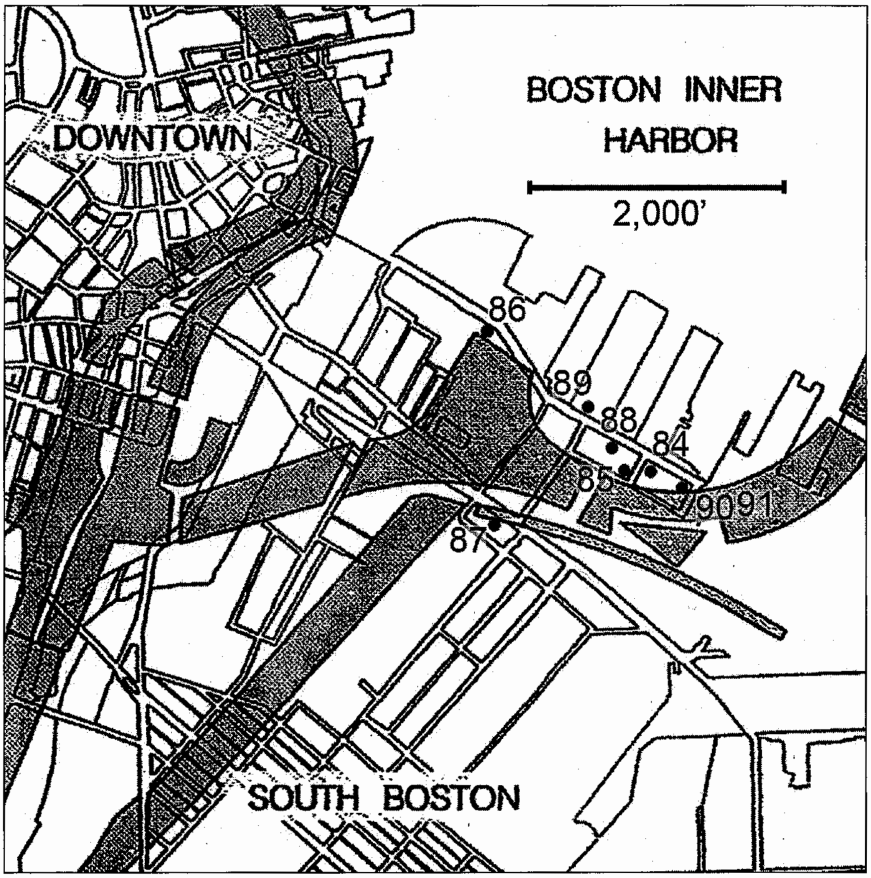


FIGURE 5-3. Map of South Boston showing the location of major buildings constructed since 1960.

One of the most historic structures in Boston is Trinity Church, which has weathered several "attacks" on its foundations. In 1872, parishioners of the first Trinity Church on Summer Street that was destroyed by a fire purchased two building lots totaling 0.367 hectares (39,487 square feet) of newly filled land in what became Copley Square (see Figure 5-6). The new church was constructed between 1872 and 1876 and consecrated in 1877. The church was designed by the renowned architect H.H. Richardson in the French Romanesque style that became known as Richardson style (see Figure 5-7). The stone used is listed by the church as Monson Granite and Longmeadow Sandstone, which is the red Triassic sandstone that was so popular at the time. However, according to Richter and Simmons (1993), Dedham Granodiorite from local quarries and Westerly Granite from Westerly, Rhode Island, also were used. The central tower weighed (Jarrett, 2012) about 8.6 million kilograms (9,500 tons).

This weight was supported by 4,500 cedar wood piles, 6 meters (30 feet) long with granite caps. The pile foundation consisted of four

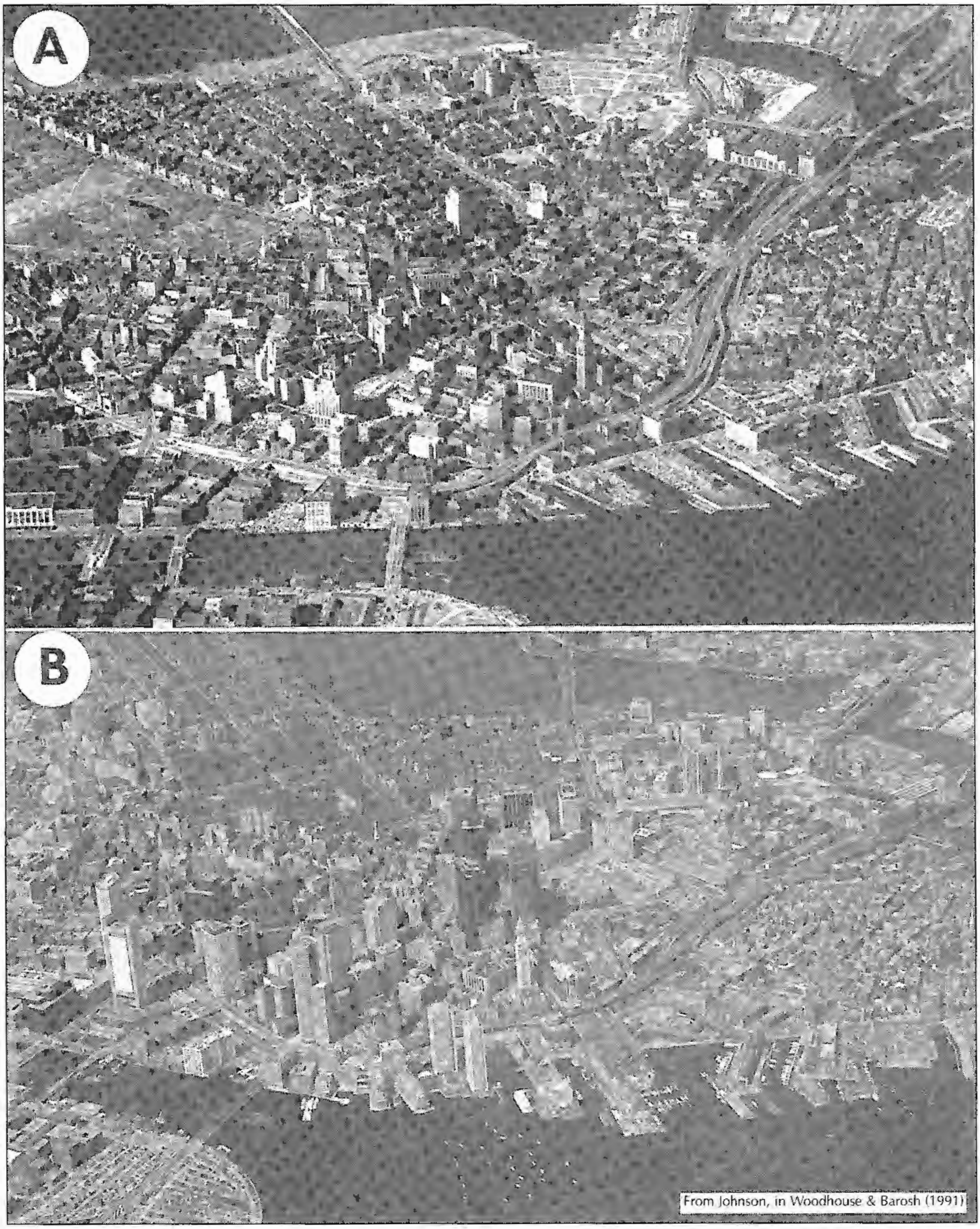


FIGURE 5-4. Aerial views of downtown Boston in (A) 1959 and (B) 1987. (Courtesy of Aerial Photos International, Inc.)

square groups, 10.7 meters (35 feet) on each side (700 piles each) that underlie pyramid-shaped granite pedestals, which serve as the bases for the four main columns of the church. (see Figure 5-8). Each 5.2 meter (17 foot) high granite pyramid is made up of granite blocks


(see color version on page 470)

FIGURE 5-5. Aerial view of Boston view on May 18, 2012. (Courtesy of lesvants.com.)

0.6 by 1.2 meters (2 by 4 feet) and 0.6 by 2.4 meters (2 by 8 feet) and is 0.65 square meters (7 square feet) at the top (see Figure 5-9). One of the granite block pile caps is exposed in the basement of Trinity Church, allowing the public to see the support for the church (see Figure 5-10).

The overburden deposits underlying the church are typical for the Back Bay. These deposits are about 6 meters (20 feet) of granular fill, organic clay and silt that extends in depth from 6 to 14 meters (20 to 45 feet), thin upper outwash sand, thick marine clay, lower outwash and till over Cambridge Argillite. The bearing stratum for the 9 meter (30 foot) long wood piles (see Figure 5-11) is either the upper outwash sand or the 1.5 meter (5 foot) thick stiff yellow clay crust of the marine clay at a depth between 13.7 to 15.2 meters (45 to 50 feet). The marine clay thickness is on the order of 24 meters (80 feet) to depths between 38 to 43 meters (125 to 140 feet); the dense strata below the clay are at a sloping surface. A 6 to 7.6 meter (20 to 25 foot) lower outwash sand and gravel underlies the clay to a depth of 44 to 50 meters (145 to 165 feet) and overlies the 3 to 4.5 meter (10 to 15 foot) thick till that extends to a depth of 44 to 55 meters (160 to 180 feet). Decomposed and weathered argillite lies at this depth.

During the time of the church's construction in the late nineteenth century, it was common practice in the Back Bay to cut off wood pile tops below the water table at an average tide level of elevation 5 feet Boston City Base (BCB). The "0" datum of BCB is set at 5.65 feet below mean sea level (MSL). Thus, the tops of the piles that were cut off at elevation 5.0 BCB or 1.5 meters (5 feet) below mean low tide have their tops at about 4 meters (13 feet) below the surrounding street grade. It was essential to keep the piles saturated in order to prevent rotting. The groundwater level in the Back Bay during the end of the nineteenth century was generally found to be at about elevation 2.4 meters (8 feet) BCB (2.48 MSL) and considered sufficient for this purpose. The pile caps at Trinity Church were originally designed with a waterway for a small boat to check water levels. A system of automatic sen-

FIGURE 5-6. Trinity Church, which was constructed from 1872 to 1876, is shown circa 1875. (Courtesy of the Boston Public Library, derived from stereograph.)

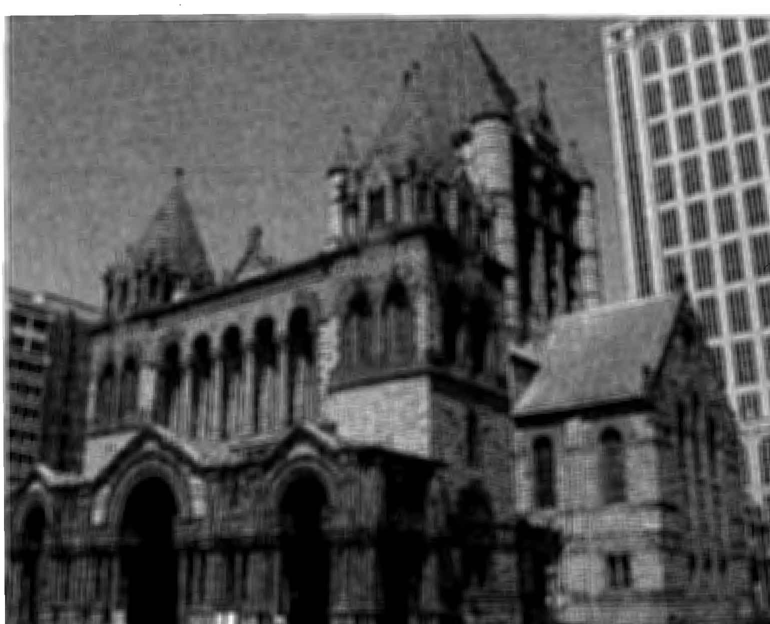


FIGURE 5-7. Trinity Church, west side of Copley Square in July 2005. (Courtesy of Mathias.)

sors now monitors the water level and water can be pumped in if it drops to a level that would affect the integrity of the piles.

The Trinity Church began to measure settlement of the central tower in the 1920s. It was found at that time that the heavy load on the wood piles had caused it to have settled about 30 centimeters (1 foot) since it was first constructed. Subsequent survey measurements found that through 1968 an additional 7.6 to 10 centimeters (3 to 4 inches) of settlement had occurred in six areas around the church. During construction of the John Hancock Tower from 1968 to 1972, differential settlement of many inches was measured along the south side closest to the tower (adjacent to St. James Avenue) and migrated horizontally toward the John Hancock excavation. This uneven settlement necessitated repairs to the church. This settlement problem also led to a lawsuit involving the John Hancock Insurance Company, for whom the tower was being built. The court found that the settlement resulted from movement of the excavation support system for the deep basement of the tower. The steel sheet pile excavation support system deflected several feet and caused considerable damage to adjacent structures, including the Trinity Church. St. James Avenue, which

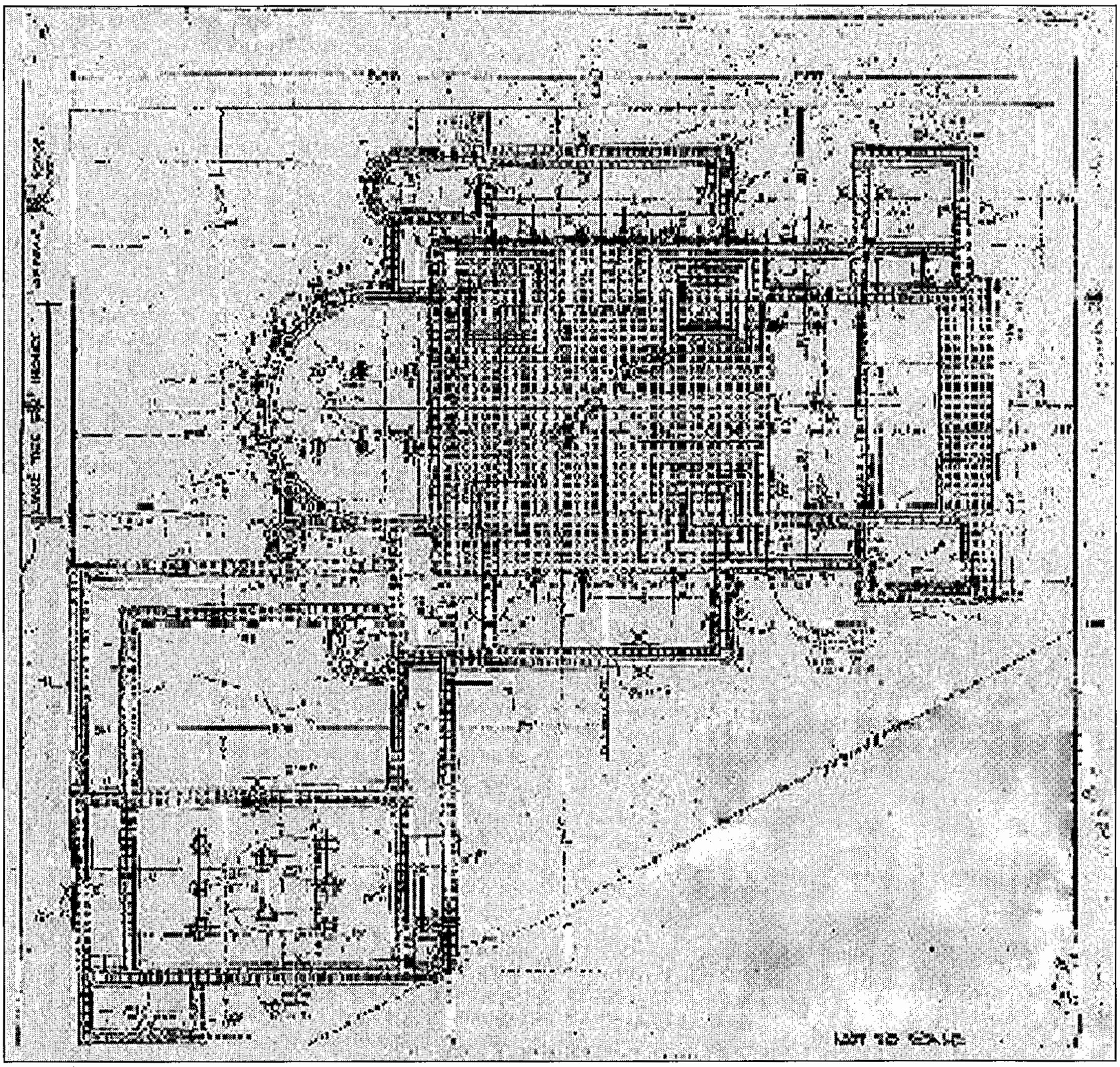


FIGURE 5-8. Trinity Church showing the plan for its pile foundation that was later augmented. (Courtesy Jean Carroon, Goody Clancy Inc.)

divides the church from the John Hancock Tower to the south, had settled more than 46 centimeters (18 inches) and lateral deflections in the tower excavation support walls were up to 110 centimeters (3 to 4 feet). Walls of the church had been pulled laterally as well and had to be knitted back together (Carroon, 2012). A list of other damage caused by the settlement were sealed by the court, as well a list of the necessary repairs effected.

Because of general concern based on the history of the church and recent issues with the John Hancock Tower, the church enacted a program from 2002 to 2005 to check the integrity and condition of the wood piles supporting the church. A number of test pits were dug to expose the condition of the piles. Wood piles that had been exposed above the groundwater level and that showed deterioration were repaired. These piles were mostly found under the church chancel. The rotted sections of the pile tops were removed and replaced by steel that was encased in concrete (see Figures 5-12 & 5-13).

Back Bay — Prudential Center. The group of buildings that comprise an area of 9.3 hectares (23 acres) generally west of Copley Square between Huntington Avenue and Boylston

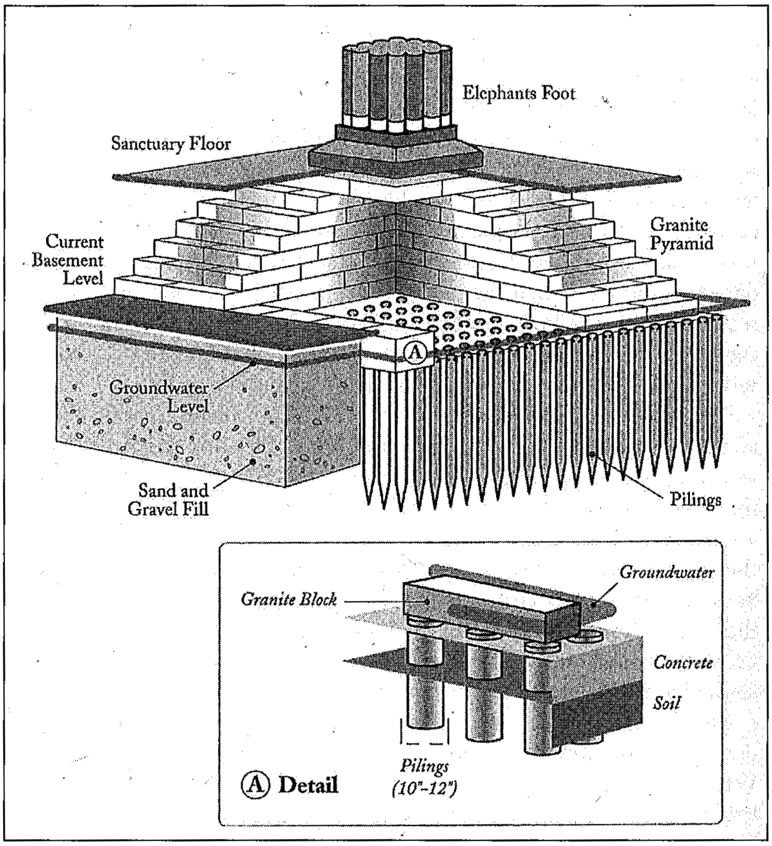


FIGURE 5-9. Trinity Church pile cap design. (Courtesy of the Globe Newspaper Company.)

FIGURE 5-10. Trinity Church basement showing the top of the pile cap approximately 2.3 m (7.5 ft) above the basement level.

Street is known as the Prudential Center (see Figure 5-2). The site was an old switchyard for the Boston and Albany Railroad from the time of original filling until the late 1950s. The complex that was constructed between 1960 and 1970 was comprised of seven buildings that included two office towers, two retail buildings, a hotel and two apartment buildings (see Table 5-1). The Prudential Center proved to be a catalyst for new development in Boston's Back Bay. The fifty-two-story Prudential Tower (built from 1960 to 1964) at 800 Boylston Street is 228 meters (749 feet) high and was the tallest building in Boston for ten years until the rival new John Hancock Tower at 241 meters (790 feet) was built. The Prudential Tower is supported by caissons drilled into the argillite. Because the bedrock was found to be weak, the caissons had to be drilled deep into the argillite, which amounted to depths from ground surface as deep as 61 meters (200 feet) (Kaye, 1982a; Ball, 1962).

The diversity of the foundation conditions in a short distance in the Prudential complex is shown by the other seven buildings in the Prudential Complex: the twenty-nine-story Sheraton Boston Hotel (built in 1962) is founded on 36 centimeter (16 inch) diameter concrete piles to till at 45 to 60 meters (150 to 200 feet); three (the Southeast Tower, Apartment 5 and the Lord & Taylor department store) are supported on concrete-filled pipe piles driven to the till or bedrock at depths up to 61 meters (200 feet); two (Apartment Buildings 1 and 3) are supported on 55 meter (180 foot) deep drilled-in caissons that penetrate into argillite; and the seventh building (originally the Sak's Fifth Avenue) is founded on a combination of Franki piles (pressure-injected footings [PIFs]) and wood piles, both bearing in the upper outwash. Other major buildings in the area of the Prudential Center include the Colonnade Hotel (built in 1971) and the Hilton Hotel (built in 1981) that were founded on deep pre-cast, pre-stressed concrete piles in concert with shallow PIFs in the outwash. Hynes Auditorium (built in 1960) used concrete-filled pipe piles driven to till or rock at a depth of 60 meters (200 feet). The Hynes Convention Center (built in 1985) expansion on Boylston Street is supported by 2,224 kilonewton (250-ton) high-capacity drilled piles into the argillite.

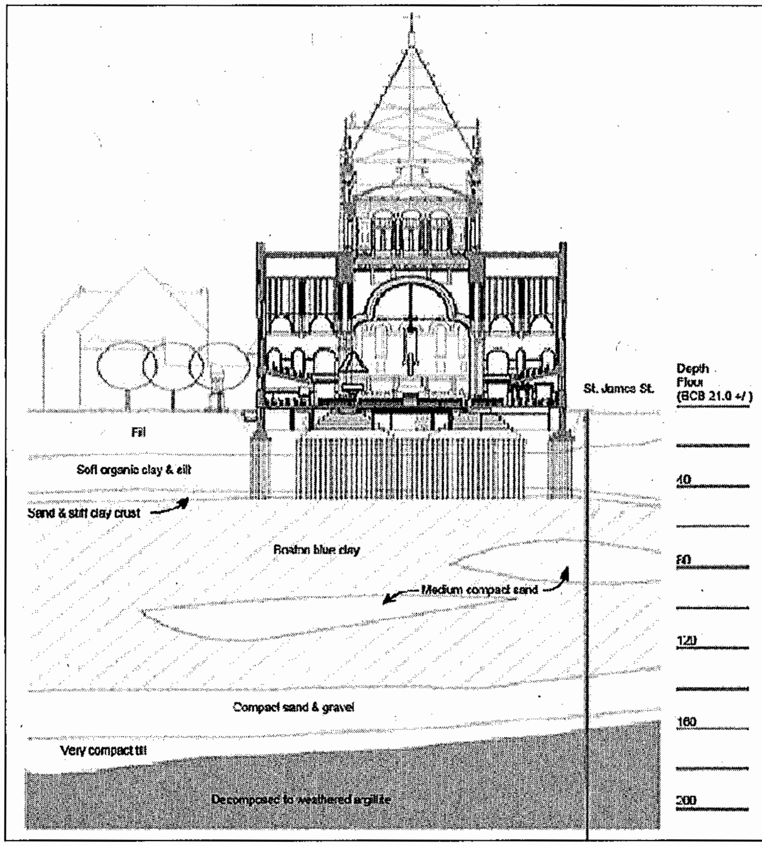


FIGURE 5-11. Section beneath the Trinity Church showing geologic units, extent of piles and geothermal well. The section consists of Cambridge Argillite, till, Lower Outwash, marine clay with weathered crust, organic deposit and fill. (Courtesy of Jean Carroon, Goody Clancy, Inc.)

The largest structure built in the Prudential Center complex since 1987 is the thirty-six-story 111 Huntington Avenue building, affectionately called the R2-D2 building (as a reference to the Star Wars droid that it resembles), which was completed in 2002. Its foundation consists of 1.2 to 1.8 meter (4 to 6 foot) diameter shafts drilled into the underlying argillite at a depth of 43 meters (140 feet). The Mandarin-Oriental Hotel is located on Boylston Street about one block away from the Boston Public Library and was constructed during the period 2005 to 2008. The complex consists of two fourteen-story towers containing apartments and condominiums with two below-ground parking levels. The smaller of the two tower structures was the first building in Boston founded on mini-piles that have a high-capacity design load of 1,957 kilonewtons (220 tons). The mini-piles were permanently cased to the argillite bedrock. The larger building has a 68 centimeter (27 inch) mat foundation bearing on the upper outwash sand at a depth of 7.6 meters (25 feet) to accommodate the garage. The mini-pile foundation was doweled into the mat for added support.

Back Bay — Christian Science Center. The Christian Science Church owns considerable property west of the Prudential Center along Huntington Avenue and Massachusetts Ave-

FIGURE 5-12. Trinity Church rotted tops of piles beneath the cap. (Courtesy of Jean Carroon, Goody Clancy, Inc.)

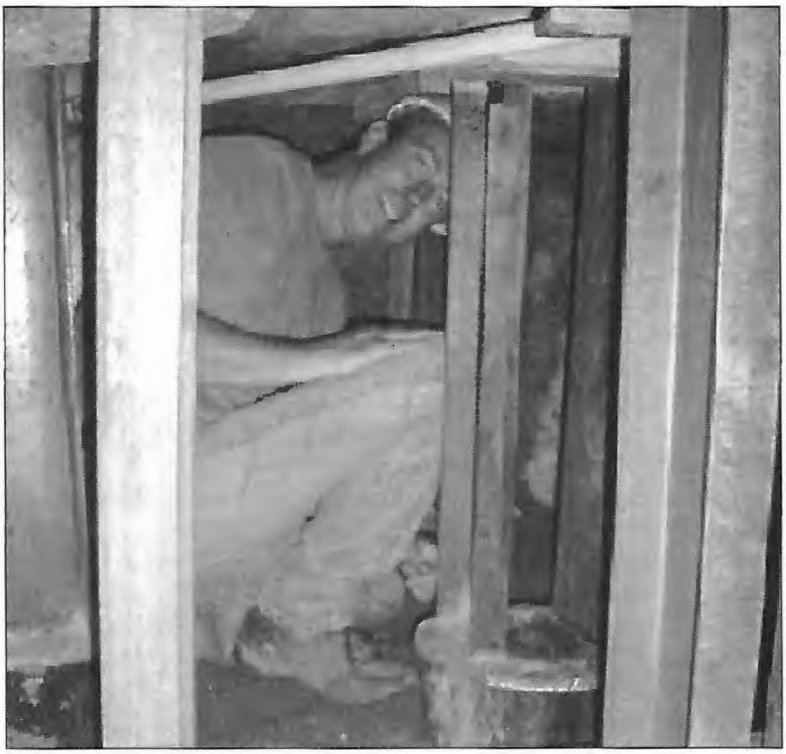


FIGURE 5-13. Trinity Church steel replacements of pile tops beneath cap. (Courtesy of Jean Carroon, Goody Clancy, Inc.)

nue, the majority of which was developed between 1968 and 1971 (see Figure 5-2). The area is underlain by the upper and lower outwash sand and gravel. The upper outwash allowed the use of PIFs in the sand to support six of the seven buildings that were up to twelve stories in height. These buildings included the five-story Sunday School Building (built in 1968), the ten-story Church Park Apartments (built in 1971), the six-story Church Park Garage (built in 1971), the twelve-story Symphony Towers (built in 1971), the five-story Colonnade Building (built in 1968) and the twelve-story Greenhouse Apartments. Because of the size and loads of the twenty-six-story Administration Building on Huntington Avenue, the structure is supported on concrete-filled pipe piles to a depth of 52 meters (170 feet). The new Mother Church was founded on end-bearing wood piles in the same outwash. When a new facade was added, it became necessary to uncover some of these old piles in order to check on their condition. The inspection revealed that a number of the piles had been pulled out of their concrete pile cap by a soil phenomenon called negative skin friction (where the surrounding soil settles and drags the pile with it). This discovery necessitated that the old foundation (concrete pile cap) be underpinned with six new concrete footings that are founded on the outwash sand that encased the top few feet of the old wood piles. Woodhouse noted that concrete was poured to within a few centimeters (inches) of the old pile cap and dry-packed with cement. Dewatering was carried out by using well points that lowered the water table in the outwash by 2.4 and 1.7 meters (8 and 5.5 feet) at distances of 12.2 and 70 meters (40 and 230 feet) from the excavation.

Back Bay & Fenway — Huntington Avenue & Longwood Medical Area. A number of new buildings have been constructed on the western campus of Northeastern University since 2000. This area at one time was a part of the Back Bay Fens and the Fenway, and along Ruggles Street there is a deep bedrock valley that was filled with marine clay. However, deep foundations have not been needed for foundations of most buildings in the West Campus complex that includes six new buildings — A through G that vary in height from four to eleven stories (Gorczyca, 2013). There are no organic soils between the surficial fill and the upper outwash (Lexington Substage). However, the top of the stiff crust of the thick marine clay is only about 3 meters (10 feet) below the ground surface. The six buildings bear on 1 to 1.2 meter (3.5 to 4 foot) thick mats on the stiff crust of the clay at depths of 2 to 6 meters (7 to 20 feet). The weight of soil/fill that was excavated counteracted the added weight of the buildings, making these examples of "floating buildings." No relief slab drainage was necessary. On the southern side of the Massachusetts Bay Transportation Authority (MBTA) Orange Line, Northeastern University's International Village complex consists of two twenty-two- to twenty-four-story tall dormitories interconnected by a five-story building. At this location, the top of the clay is 6 to 7.5 meters (20 to 25 feet) deep. A mat foundation bearing on the crust of the thick marine clay, similar to that at the West Campus, was used for the dormitory towers. The interconnecting building is supported by PIFs bearing in the upper outwash above the clay.

The building at 541-555 Huntington Avenue is a seven-story residence hall constructed in 2003 at the Wentworth Institute of Technology. The building is founded on a combination of belled caissons and drilled mini-piles on the eastern site portion where the Metropolitan Water Resources Authority/Metropolitan District Commission (MWRA/MDC) Muddy River sewer easement is located (Hover, 2013). Subsurface conditions consist of up to 6 meters (20 feet) of fill overlying a 3 to 4.5 meter (10 to 15 foot) thick organic layer. The upper outwash sand and gravel with a thickness of 0.5 to 2 meters (1.5 to 7 feet) underlies the organics, which in turn overlies the marine clay. The clay was found to be up to 26 meters (85 feet) thick from a depth between 8 and 9.5 meters (26 and 31 feet), with the bottom of the layer at 34.5 meters (113 feet). At this location, the lower outwash sand was encountered, but it was not fully penetrated by the test borings. The Boston Society of Civil Engineers (BSCE) boring logs show the top of bedrock at about 33.5 meters (110 feet), but one of the borings reached 36.5 meters (120 feet) without encountering bedrock. Design engineers took advantage of the 3 to 6 meter (10 to 20 foot) thick hard crust in the yellow clay and installed belled caissons in the upper 3 meters (10 feet) with a bearing capacity of 479 kilonewtons per square meter (5 tons per square foot). The caissons were from 2.4 to 3.5 meters (8 to 11.5 feet) in diameter with shafts of 1.8 to 2.1 meters (6 to 7 feet). Drilled 25 centimeter (10 inch) diameter mini-piles with a 356 kilonewton (40 ton) capacity were installed 6 to 7.5 meters (20 to 25 feet) into the clay on the eastern side. Total pile length was 13.7 to 16.8 meters (45 to 55 feet) with a skin friction of 72 kilonewtons per square meter (1,500 pounds per square foot) and 5 tons per pile were allowed for downdrag from negative skin friction.

The MassArt Tower at 621 Huntington Avenue, located about two blocks west of the Museum of Fine Arts, was built between 2010 and 2012. The foundation for the tower consists of HP 14x117 steel piles driven to a depth of 41 to 55 meters (135 to 180 feet) to the argillite. Very dense soils were encountered at a depth of 31 meters (100 feet). However, the piles were driven through these soils to bedrock for the necessary end bearing.

Farther west along Huntington Avenue is the Longwood Medical Area (LMA), a famous medical campus in Boston that forms a triangular area bounded in broad terms by the Muddy River, Huntington Avenue and the Fenway. The LMA is centered on the main thoroughfares of Longwood Avenue and Brookline Avenue as they run from Huntington Avenue to the Riverway. It is strongly associated with the Harvard Medical School and related medical facilities, such as Harvard's teaching hospitals, but prominent non-Harvard and non-medical institutions are located there as well. The Longwood area was formerly a swampy, tidal area associated with the Muddy River where it entered the Charles River in colonial times.

In the area of the Muddy River, deep sediments fill an ancient bedrock valley that reaches a bottom elevation of about –65 meters (–200 feet) MSL (Kaye, 1970 & 1982b). In this valley, the foundation investigation for the Beth Israel Feldberg Building at the corner of Longwood Avenue and Brookline Avenue (GEI, 1972) found in descending order 4.5 to 7.5 meters (15 to 25 feet) of granular materials, cinders, bricks, peat and wood; up to 1.5 meters (5 feet) of peat and organic sand below; clay and silty fine sand up to 21 meters (70 feet) thick; till 12 to 17 meters (40 to 55 feet) thick with lenses of varved, lacustrine silt and clay sediment possibly representing local ponding during original deposition. Argillite bedrock at this particular location was encountered at a depth of 45 meters (128 feet). In the Muddy River/Fens area, deep end-bearing piles would be expected to be the foundation of choice for tall, heavy buildings.

Along the southwest area of the LMA, the topography rises onto the northern slope of the Parker Hill/Mission Hill drumlin. At this location, the shallow till offers a competent bearing material for footings and mat slabs. As the Riverway (Muddy River) is approached to the west, Woodhouse has noted that outwash sands are known to overlie the clay.

Hospital and research institutions have constructed several new buildings since the late 1990s in the LMA, where the foundation used depends on the building's location.

At the Longwood Center at Brookline and Longwood avenues, in an area of thick clay, a deep foundation was used for the eleven-story medical building for the Dana Farber Cancer Institute and the Longwood Medical Eye Center (adjacent to the Joslin Diabetes Center). The Boston Children's Hospital expansion is a ten-story facility (to be completed in 2013) located at 57 Binney Street, diagonally across from the Feldberg Building (where pile foundations were used). The Beth Israel Deaconess Medical Center is building an eighteen-story facility at Blackfan Street and Longwood Avenue, located just southeast of the Feldberg Building with the similar subsurface conditions and deep foundations. This building is scheduled to be completed in 2014.

Subsurface conditions change markedly at sites uphill from the Muddy River Valley. Brigham and Women's Hospital, at the north end of Parker Hill, which is underlain by shallow till, used shallow footings for a new clinic and laboratory building. Shallow footings were also used for the uphill Mass Eye and Ear, a six-story building at 800 Huntington Avenue, and for Harvard Medical at 25 Shattuck Street (to be occupied by Beth Israel Deaconess and the Dana Farber Cancer Institute).

Downtown Boston & Waterfront. The first wave of new development (concurrent with Back Bay — Copley Square and Prudential Center) began on the original Shawmut Peninsula in 1965 with the construction of the New England Merchants Bank Building on State Street and was soon followed in 1966 by the State Street Bank on Franklin Street (see Figure 5-2). In 1968, the innovative Boston Company Building, a forty-one-story office building located on a 0.344 hectare (37,000 square foot) plot at the southwest corner of Washington and Court streets, began construction and was completed in 1970 (see Figures 3-82 & 5-14). The site is located on the east slope of Beacon Hill and is within the limits of the original colonial shoreline of the Shawmut Peninsula. The site is underlain by deformed and faulted clay, sand and gravel, and till, representing the overthrusted Beacon Hill sediments. The central core foundation used a uniform, reinforced concrete mat bearing on the compact sand and

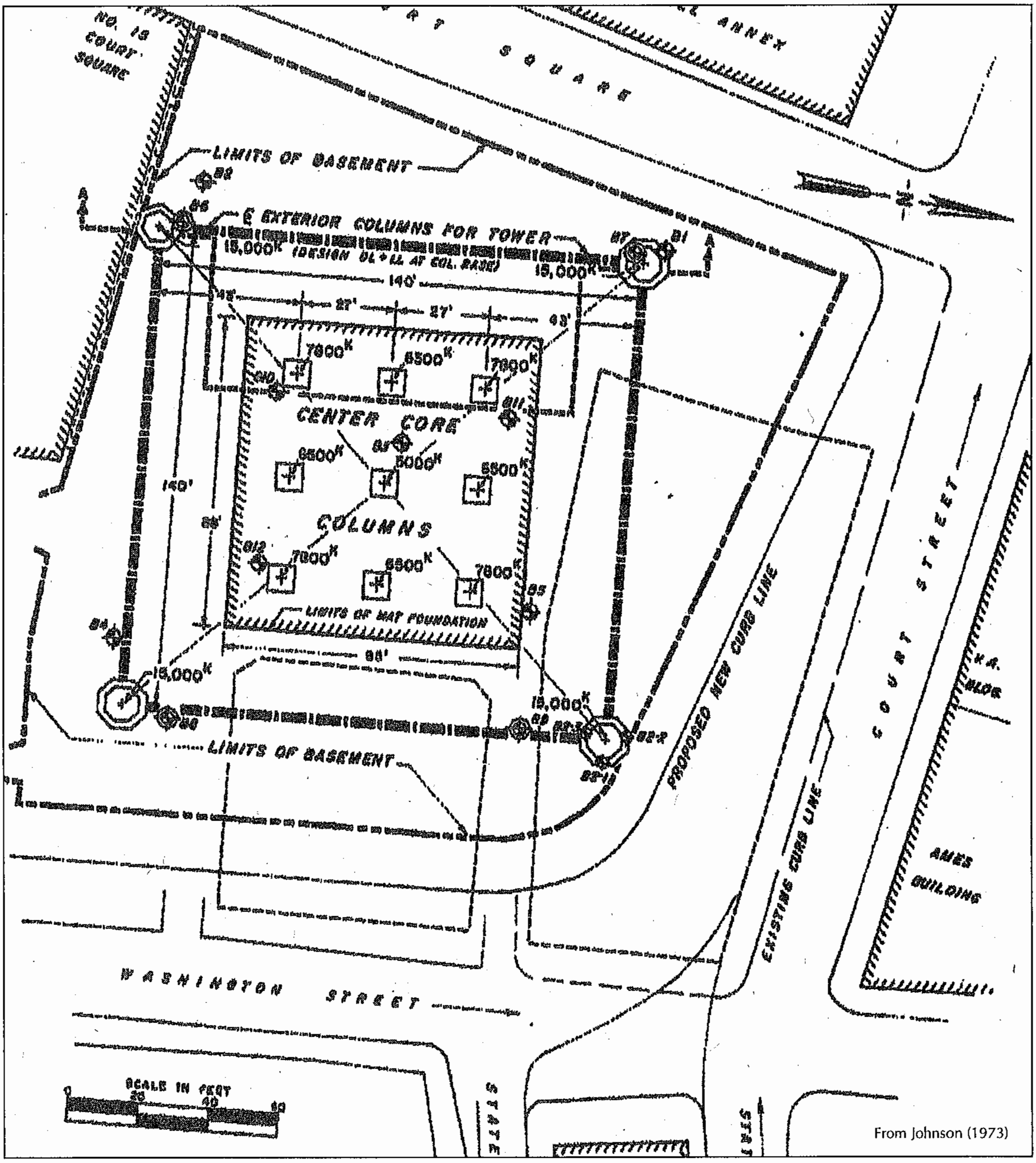
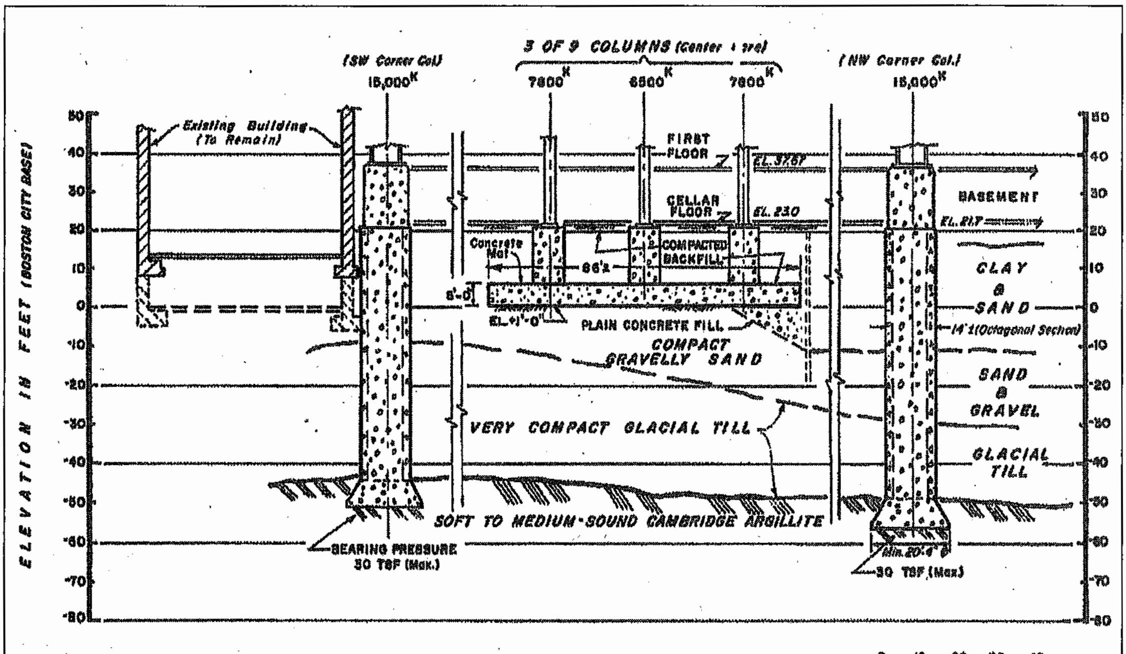


FIGURE 5-14. Foundation plan for the Boston Company Building.

gravel stratum at a maximum gross bearing pressure of 527 kilonewtons per square meter (5.5 tons per square foot). Where necessary, the marine clay overlying the sand was excavated and replaced with a mass pour of lean concrete fill to the limits specified. Each of the four very heavily loaded corner columns was founded on a large-diameter pier caisson with an enlarged bearing area supported on, or within, the argillite (see Figures 5-14, 5-15 & 5-16), some 15 meters (50 feet) below the central core mat (Johnson, 1973). The gross design end-bearing pressure on the rock surface was 2,873 kilonewtons per square meter (30 tons per square foot), with adequate provision for enlarging the bearing area and reducing the bearing intensity during construction, if necessary, to account for possible variations in rock



From Johnson (1973)

FIGURE 5-15. Typical geology and foundation geometry and column design loads for the Boston Company Building (view west).

quality (see Figure 5-17). The minimum structural pier section was based on a design compressive stress of 4,826 kilonewtons per square meter (700 pounds per square inch) for unreinforced concrete (per a 1970 Boston Building Code restriction).

In 1969, urban development moved to the waterfront along Atlantic Avenue and Commercial Street between the North End and South Station. At that time, the area was made up of old brick and granite block warehouses used primarily for refrigeration. Developers realized that young urban professionals saw these old buildings as very desirable as living spaces and converted them to condominiums. New space was also sought at the edge of the harbor, which brought challenges for the geotechnical community because the waterfront lay just beyond the old colonial shoreline and was underlain by thick deposits composed of fill, organic deposit, marine clay and glaciomarine deposit, lower outwash and till. Dealing with the fill was in itself a challenge because of the old buried granite block seawalls, which necessitated judicial use of historical maps when locating test borings. The construction in 1969 of the two forty-story-tall high-rise apartment buildings (later condominiums) known as Harbor Towers initiated redevelopment on Atlantic Avenue. The foundation consists of concrete-filled steel pipe piles driven to end bearing in the till at a depth of 18 to 27 meters (60 to 90 feet). More than a decade later, the Long Wharf Marriott on Atlantic Avenue was built between 1981 and 1985 using pre-cast, prestressed concrete piles driven to the till (which had come into common use instead of the concrete-filled pipe piles).

The Rowes Wharf Development on Atlantic Avenue, known as the Boston Harbor Hotel, is a fifteen-story office and hotel structure with five levels below and is founded on caissons belled in till. The foundation design included a slurry wall and was the first project in Boston to use the "up-down" construction technique (see Figure 5-18). The ten-story building constructed in 1987 at 745 Atlantic Avenue with its three levels below grade is founded on a concrete mat bearing on sand.

The U.S. Coast Guard EMS building located in the North End on Commercial Street (a continuation of Atlantic Avenue) is noteworthy because it has a new structural mat over existing wood piles, plus additional prestressed concrete piles driven to the till.

Geotechnical engineers took advantage of the underlying till at shallow depths on the Shawmut Peninsula that were capable of high-capacity bearing loads. Subsequently in the 1970s, the banking and insurance community further strengthened their faith in Boston by building several major high-rise office buildings in the downtown area between Tremont Street and South Station, along with considerable construction activity on the waterfront. This area incorporated the original shoreline of Boston, the remaining high ground and nearby filled land. The deposits encountered included fill, organic deposit, marine clay, lower outwash, glaciomarine and mixed overthrust deltaic and outwash deposit, and till. The argillite surface was encountered as deep as 30 meters (100 feet), between elevation –15 and –30 meters (–50 and –100 feet) MSL. Building heights varied between thirty and forty stories and most were supported by mats and footings on the till and overthrust deposits. These buildings included One Beacon Street, the First National Bank and the Shawmut Bank on Federal Street. The 60 State Street building used an innovative hybrid foundation comprised of a mat and caissons along with concrete slurry walls for excavation support. The building at One Post Office Square used PIFs in the till (see Figure 5-19).

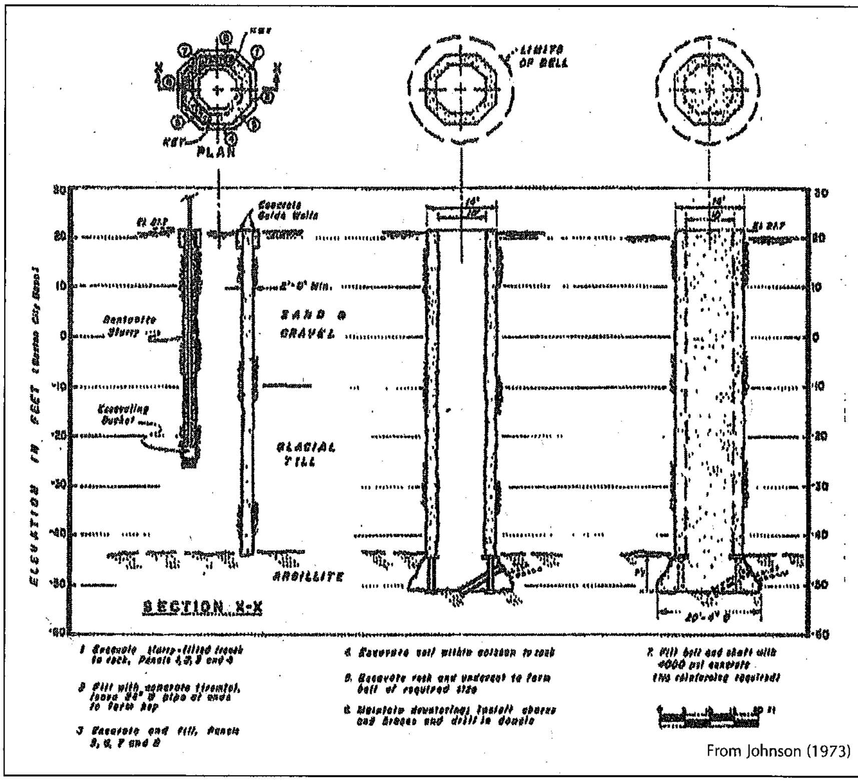


FIGURE 5-16. Construction procedures for corner piers for the Boston Company Building.

The decade of the 1980s saw continued development along State Street and in the Financial District around Federal Street. Deep excavations for up to six levels of underground parking have been common to meet the needs of a growing city. However, there was an additional benefit to digging so deep since it brought the foundations into the high-bearing capacity till where mats and footings could safely be used. Building heights reached forty-six stories such as International Place at the end of High Street. Office buildings at 260 and 265 Franklin Street, South Milk Street, One Devonshire Place and International Place were constructed on thick concrete mats and footings bearing on the till. Certain design considerations required hybrid foundations of mats or footings in combination with concrete-filled pipe piles such as at Lafayette Place on Washing-

FIGURE 5-17. Typical condition of argillite at the base of a pier for the Boston Company Building.

ton Street and 53 State Street. At 75 State Street, six underground levels necessitated the use of caissons in the argillite. The ten-story O'Neill Government Services Building constructed in 1985 next to North Station on Causeway Street used a foundation consisting of both pre-stressed concrete piles and steel H-piles.

The thirty-three-story office building at 33 Arch Street completed in 2004 has a foundation consisting of 2.4 to 3.7 meter (8 to 12 foot) diameter shafts drilled 3 to 10.7 meters (10 to 35 feet) into competent argillite at depths between 21 and 38 meters (70 and 125 feet). The stratigraphy encountered consists of up to 4 meters (14 feet) of fill overlying marine clay 1 to 11 meters (3.5 to 31 feet) thick that contained layers of sand and gravel with cobbles and boulders. Below the clay, a 4 to 13 meter (13.5 to 43 foot) layer of dense silt containing sand, gravel and cobbles (described as a glaciomarine deposit) overlies the bedrock. The bedrock consisted of weathered and decomposed argillite at elevations between –25 and –34 meters (–82 to –112 feet) BCB and at depths of 12 to 19 meters (38 to 63 feet). The thickness of the decomposed rock ranged from 4.5 to 14.5 meters (14.5 to 48 feet). This site exemplifies the difficulty in describing the marine clay, glaciomarine and (what may be) till deposits when they occur on a site together and have similar compositions.

The Atlantic Wharf redevelopment included the up-down construction of a thirty-one-story mixed-use tower with six levels of below-grade parking along the historic Boston Harbor waterfront (Haley & Aldrich, 2002). The site was formerly known as Russia Wharf and the construction had to address the former waterfront structures (granite block seawalls, numerous timber piles and old pier structures), weak sub-surface soil conditions, tidal groundwater levels and contaminated soils resulting from previous site usage and filling. The foundation system consisted of heavily loaded drilled shafts and a concrete diaphragm, or slurry wall. The project was required to preserve portions of the facades of former historic buildings. Below-grade construction was completed in March 2010. The overburden conditions beneath the site generally consisted of a fill layer 3 to 7.3 meters (10 to 24 feet) thick overlying organic deposit 1.8

to 4 meters (6 to 13 feet) thick, marine clay 8.5 to 18.6 meters (28 to 61 feet) thick, till 1.2 to 7 meters (4 to 23 feet) thick and bedrock 21.3 to 30 meters (70 to 98 feet) below the ground surface. The bedrock at the site consisted of the Cambridge Argillite formation that was typically highly to completely weathered.

Drilled shafts form the foundation support system, with a concrete diaphragm wall that provides permanent lateral support of the below-grade space. Design parameters of 0.10 kilopascals (5 kips per square foot) inside friction and 0.84 kilopascals (40 kips per square foot) in end bearing were chosen for the design of the drilled shafts. A total of thirty-three drilled shafts ranging from 1.2 to 2.7 meters (4 to 9 feet) in diameter were installed to support the building. The shafts supporting the concrete core were 2.7 meters (9 feet) in diameter, with approximately 20.7 to 23.5 meters (68 to 83 feet) rock sockets, while the shafts supporting the perimeter tower and low-rise columns ranged from 1.2 to 2.1 meters (4 to 7 feet) in diameter, with rock sockets ranging from approximately 2.4 to 18.3 meters (8 to 60 feet).

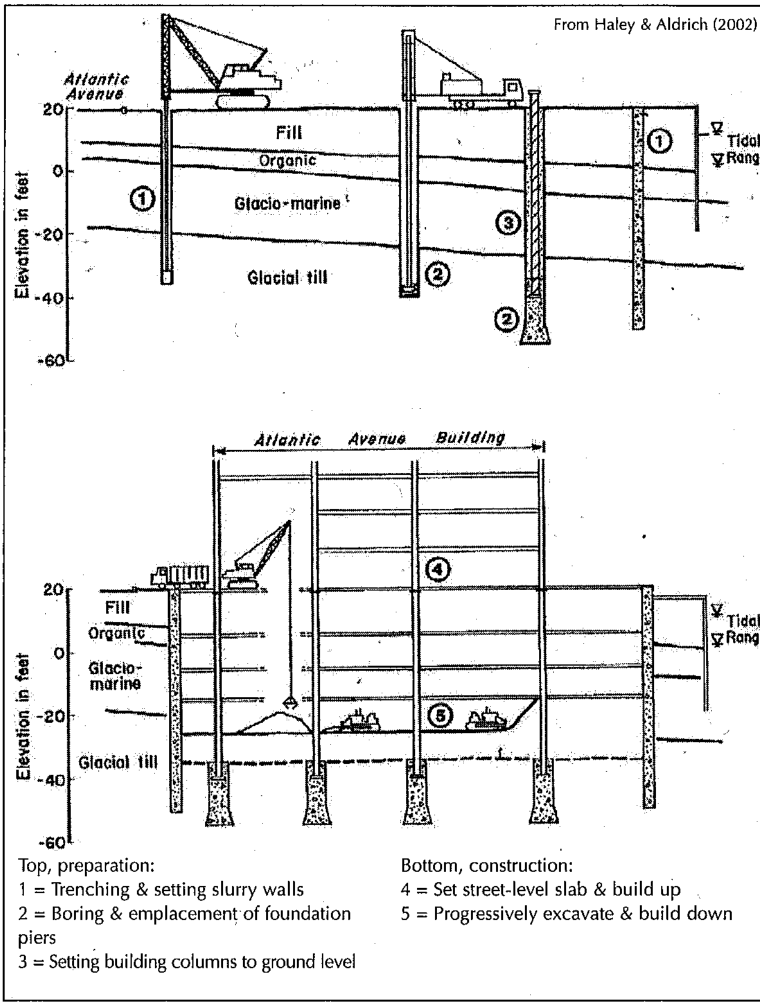


FIGURE 5-18. Up-down construction for the Rowes Wharf Project showing the construction sequence.

A number of new buildings have been proposed in the downtown and South Station areas. One of potentially spectacular significance is a proposed 305 meter (1,000 foot) tall tower. For future considerations, an extensive drilling program was conducted at the proposed Trans National Place in Winthrop Square between Federal and Devonshire streets. The drilling reveals and serves as an example of the type of complex geology that may be encountered in exploring for deep foundations in Boston. Boreholes have been drilled to as deep as 65.5 meters (215 feet). These borings intersected a soft, highly to slightly weathered gray argillite with some tuffaceous and sandstone interbeds as well as quartz veins below a depth of 20.4 to 24.6 meters (67 to 81 feet) at elevation –10 to –15 meters (–33 to –49 feet) MSL that became only slightly weathered and harder with deepening (O'Hara & Haley, 2007). The very thinly layered bedding is moderately to vertically dipping. A borehole in the middle of the west side of the site intersected a breccia zone at –23 to –26 meters (–76 to –86 feet) MSL and several thin brecciated shear zones lie below indicating faults below the site. The bedrock surface shows a trough extending northeastward across the site toward the shore, as indicated by the boring data combined with those compiled by Kaye (1970). The argillite is covered by 1.5 to 6.3 meters (0.5 to 20.5 feet) of till comprised of gray gravelly silt with few cobbles and boulders. The till is overlain by 0 to 8.4 meters (0 to 27.5 feet) of glaciomarine sediment described as hard, gray clay with some amount of fine to coarse sand and gravel. Stiff yellow-brown (the weathered crust) to gray soft marine clay with scattered seams of fine sand and sandy silt 5.8 to 15.4 meters (19 to 50.5 feet) thick exists over the glaciomarine sediment. A 1.5 to 4 meter (5 to 13 foot) thickness of miscellaneous fill caps the site. The boring samples at this location demonstrate the difficulty in distinguishing till from glaciomarine sediment. The glaciomarine deposit pinches out to the north side of this site, apparently due to a later channel, which was subsequently filled by the marine clay and later acted as a guide for the formation of the tidal creek.

Up-Down Construction Technique. Increases in the value of urban sites during the building booms of the 1980s and 1990s made constructing underground space more economically attractive, particularly in congested areas. The application of the "up-down" or "top-down" construction method in Boston offered advantages for certain difficult site and subsurface conditions, as described by Haley & Aldrich, Inc. (2002). The up-down method allowed for the simultaneous construction of a project's substructure and superstructure. This approach evolved in Europe from the "Milan method" for subway construction, which has been described as "cover-then-cut" — that is, parallel slurry walls are installed and then a bridge between the slurry walls is constructed and decked over for traffic. Of note is the fact that this method was used in an early form for urban tunnel construction in several cities. In Boston, it was used for the Summer Street/Winter Street subway construction from 1912 to 1914. For this project, the street was opened, decked and returned to surface traffic while the subway tunnel was excavated and constructed below. Slurry walls were not used then. The soil was then mined from underneath the decking to create space for the tunnel structure.

Up-down construction (see Figure 5-18, top) involves the installation of the substructure's walls, below-grade columns and foundation system from the ground surface prior to excavation (Haley & Aldrich, 2002). Concrete diaphragm walls constructed using the slurry trench methods are typically also incorporated as the perimeter basement walls. They serve the dual purpose of lateral excavation support during construction and as perimeter walls for the final structure. After the perimeter walls are completed, the structure's columns and foundation elements are installed from the existing ground surface. Then excavation begins and the substructure's floor system is installed as each level of excavation is reached. These floors also serve the function of cross-lot braces during construc-

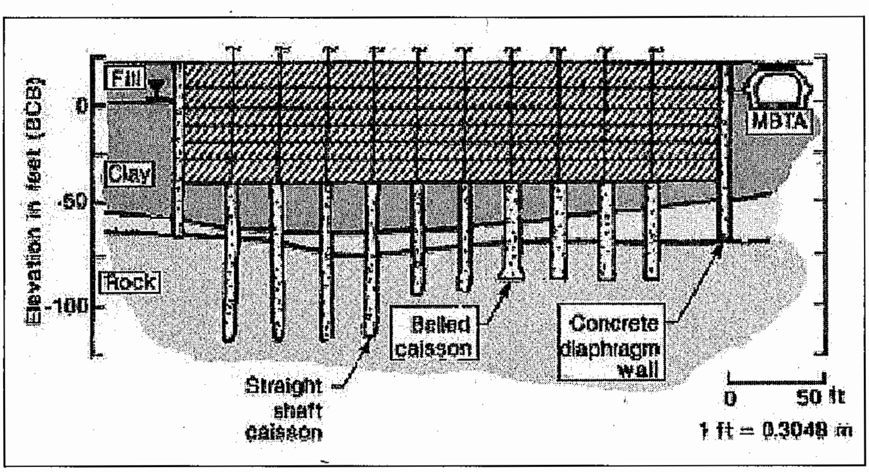


FIGURE 5-19. Section at the side of Post Office Square Garage showing lithology and slurry wall for up-down construction of seven sub-floors. (Courtesy of Deep Excavations, LLC.)

tion by providing lateral support to the diaphragm walls as the excavation proceeds downward by mining the soil below the lowest installed floor level (see Figure 5-18, bottom). At the same time the excavation proceeds downward, the superstructure is erected. The concrete diaphragm wall is typically 1 meters (3 feet) thick and provides a stiffer system than conventional steel sheeting and shoring schemes, and can result in reducing the lateral movements of the support system during construction.

The first up-down project performed on the East Coast was the Rowes Wharf Boston Harbor Hotel Project in Boston from 1985 to 1987. The $193 million Rowes Wharf Project is a mixed-use development located on a narrow strip of land adjacent to Boston Harbor with twin fifteen-story towers and five levels of below-grade parking. The challenging site and subsurface conditions dictated a creative construction procedure such as that offered by the up-down construction technique.

Since 1985, up-down developments in downtown Boston have included Millennium Place, Massachusetts General Hospital, Charles River Plaza North and South, 125 Summer Street, 75 State Street and Russia Wharf. Outside the downtown area, the technique was used for the Center for Life Sciences on Longwood Avenue, a twenty-one-story building with six levels below grade and supported by 2.4 to 3 meter (8 to 10 foot) diameter slurry caissons at a 40 meter (130 foot) depth.

The Russia Wharf building complex on Atlantic Avenue is a thirty-two-story hotel, condo and office building that was constructed between 2007 and 2010. Because of the historical nature of the site, the seven-story exterior of the building was preserved by using the slurry wall both to support and hang the facade. The new MBTA Silver Line Tunnel passes underneath the building. The foundation consists of the existing wood piles in the marine clay that were load tested in conjunction with ground freezing and underpinning with mini-piles bearing on the till.

The twenty-two-story Intercontinental Hotel at 510 Atlantic Avenue was completed in 2006 and is unique in that it is wrapped around the new vent shaft for the adjacent new Central Artery Tunnel. The building contains two 72 meter (237 foot) high concrete towers. Support for the hotel consisted of the existing vent shaft foundations, a 0.76 meter (2.5 foot) thick slurry wall keyed into the till constructed as a cutoff wall and for foundation support, drilled caissons in the argillite and pre-cast, pre-stressed concrete piles for the new wharf.

Park Square — Boston Common Area. Except for the Tremont-on-the-Common (built in 1963) and the Under Common Garage (built in the early 1960s), new projects in the Park Square and Boston Common-Public Gardens areas were developed in the 1980s. The excavation for the Boston Common Garage was 14 meters (45 feet) deep and encountered fill and deformed sediments (Kaye, 1961). Located along the original shore and adjacent tidal flats of the Shawmut Peninsula on what is now Charles Street, excavation on the west side of the garage encountered granular and cinder fill overlying peat and sediment upon which a colonial era boardwalk had been constructed. During the excavation in 1961, water-bearing sand and gravel that had been glacially folded and thrusted upward was encountered and caused excavation flooding (see Figure 3-83). A dewatering system comprising well points was installed to control the flooding. Construction of the concrete foundation slab then continued without further incident.

Shallow marine deposits were found suitable for mat foundations for the State Transportation Building (eight stories) in Park Square, 500 Boylston Street (twenty-five stories) and the Heritage on the Garden (twelve stories) on Boylston Street. Foundation conditions were expected to be variable for the projects located in the area of Beacon Hill because it was known to be underlain by glacially disturbed, heterogeneous deposits. Foundation types used have been variable. PIFs have been founded in sand that occurs in the marine deposits, which was the case of the Four Seasons Hotel (thirteen stories) on Boylston Street. PIFs and pre-cast, pre-stressed concrete piles bearing in marine deposits were used for the old Ritz Carlton Hotel and Garage (now the Taj Boston) at Arlington and Newbury streets. Concrete-filled pipe piles driven to till were used for the Tremont-on-the-Common (Johnson, in Woodhouse & Barosh, 1991).

Millennium Place Buildings I, II and III (which include the new Ritz-Carlton Hotel and two towers of thirty-six and thirty-eight stories) were constructed from 2001 to 2012 on Avery Street at the corner of Tremont and Boylston streets. The up-down construction method was used to construct Buildings I and II, and these were supported on LBEs. A mat foundation was used for Building III. All foundations bear on deformed sand and clay that are similar to those found under Beacon Hill. These soil deposits were exposed in the foundation excavation (see Figure 3-84).

The Millennium Place III project (constructed in 2012 and 2013) is a fifteen-story residential tower located on Hayward Place in the Downtown Crossing/Chinatown area of downtown Boston. The building is located on the northern edge of the original Boston Neck, an area formed of an elevated clay ridge and deformed overthrust deposits. The foundation consists of a split system due to the proximity of the Orange Line along Washington Street. The support for the excavation consisted of soldier pile and lagging with one level of internal bracing. The split building foundation includes a mat bearing on the natural glacial soils for about 75 percent of the building and along Washington Street, 0.9 and 1.2 meter (3 and 4 foot) diameter drilled shafts about 24 meters (80 feet) deep bearing in the weathered argillite.

The thirty-one-story residential building at 45 Province Street is located east of the Boston Common on what is now the southeast slope of Beacon Hill. Foundations consisted of 1.2 meter (4 foot) diameter caissons drilled through the till to a depth of 18 to 23 meters (60 to 75 feet) below grade.

Government Center Area. In the late 1950s and early 1960s, the notorious Scollay Square area and most of the historical West End were demolished to make way for new modern developments that included the original Central Artery elevated highway, Charles River Park Apartments and the Government Center complex that was built between 1963 and 1970. The modernistic Boston City Hall and several major office buildings that house federal and state agencies were constructed. Development took place on what was the east side of the old Trimountain (Beacon Hill) that was originally high ground in colonial times. The West End is unlike all other areas of central Boston in that the bedrock is shallow and locally crops out. Geologic conditions ranged from the shallow bedrock to mixed deposits of sand, marine clay, till and glaciomarine material. The variable geology presented the foundation engineer and geologist with several design options for each building and the opportunity to take advantage of the shallow nature of the bearing materials. Foundations used in this area consist of mats on the till for the twenty-five-story JFK Office Building, footings and mats on the glaciomarine deposits for the eight-story Center Plaza, concrete-filled pipe piles driven into the till to support the sixteen-story Saltonstall State Office Building and City Hall, and drilled rock-socketed caissons for the eight-story tall State Services Center on New Chardon Street.

Charles River Park & Massachusetts General Hospital Area. During the periods from 1960 to 1962 and from 1973 to 1974, the area north of Beacon Hill and south of the mouth of the Charles River that incorporated a portion of the old West End was developed. Nine apartment buildings ten to thirty-six stories tall were developed as the Charles River Park and Longfellow Place. In this area, the presence of compact and thick upper outwash sand allowed the use of PIFs and spread footings. Footings were also founded on shallow argillite. The thirty-six-story Longfellow Place at Leverett Circle sits on spread footings on the rock. Where the rock dropped off, deeper foundations consisted of concrete-filled pipe piles and drilled caissons. In the Massachusetts General Hospital (MGH) area, bounded by Charles and Cambridge streets, medical facilities were constructed between 1968 and 1969, as well as between 1979 and 1980. These buildings are founded on composite and concrete-filled pipe piles driven to the till at a depth of 24 meters (80 feet), on PIFs in the lower outwash sand and till, and on caissons belled in the marine clay.

The fourteen-story MGH Lunder Building with three levels 15 meters (50 feet) below grade was constructed at the corner of Fruit Street and North Grove Street and opened in 2011. Its construction involved the use of the up-down building method with a perimeter slurry wall. The interior columns were founded on 1.2 meter (4 foot) diameter caissons drilled into the till and the argillite bedrock.

South End/Chinatown. In this area south of Kneeland and Stuart streets, the overburden is undeformed and allows foundations for intermediate height buildings to use the stiff crust on the marine clay for bearing. The Tufts Health, Education and Science facility on Harrison Avenue is supported on a concrete mat on the marine clay. Bradford Towers on Stuart and Tremont streets consisted of five buildings four to nine stories high supported by footings and caissons on or in the marine clay. Some of the caissons were deep because of the close proximity of the Orange Line subway. Tufts' New England Medical Center expanded in the period from 1978 to 1984 with the construction of the nine-story medical facility on Stuart Street, which used pre-cast concrete piles driven to bedrock to accommodate high column loads. The ten-story Wang Laboratories on Kneeland Street is supported by deep pre-cast concrete piles to 38 meters (125 feet). The twenty-eight-story Park Essex now called the Boston Common at 600/660 Washington Street is founded on drilled-in concrete caissons to depth of 34 meters (110 feet) with 3 to 4.5 meter (10 to 15 foot) diameter sockets drilled into the argillite. A 1 meter (3 foot) thick concrete mat at a depth of 8 meters (25 feet) below the street level is supported by these caissons.

South Station-Dewey Square. From 1967 to the present, major construction has taken place in the Dewey Square-South Station area generally bounded on the north by Oliver Street and Seaport Avenue, on the northeast by Atlantic Avenue, to the south and southeast by Fort Point Channel, to the west by the surface artery street that forms the end of the downtown and to the southwest by Beach Street. A major portion of the new Central Artery Tunnel underlies this important junction. The high bearing capacity of the shallow till, representing the remnant of the excavated Fort Hill drumlin, allows the use of concrete mats and footings to support large structures. These buildings include the forty-six-story One Financial Center, thirty-five-story Federal Reserve Bank, twenty-eight-story 150 Federal Street, twenty-two-story 99 Summer Street and the thirty-two-story Keystone Building at 225 Congress Street.

The South Postal Annex and Stone and Webster buildings on Summer Street used concrete-filled pipe piles driven to till and bedrock. Caissons bearing in the till or socketed in bedrock support 101 Federal Street, 101 Arch Street, 100 Summer Street, 125 Summer Street and 175 Federal Street. One Lincoln Street is a thirty-six-story office tower built in the Dewey Square-South Station area and completed in 2003. The building used up-down construction and includes five parking levels below ground that necessitated an excavation depth of 17 to 20 meters (55 to 65 feet). The perimeter slurry wall, which is keyed into the till, is used for groundwater cutoff and became a permanent foundation wall. The interior columns have footings founded on the till.

Seaport Areas of South Boston. Development since the year 2000 (see Figure 5-3) has continued in earnest across the Fort Point Channel from downtown and South Station into the area now called the Seaport in South Boston. This area extends along Northern Avenue (now Seaport Avenue), Congress Street and Summer Street. The region was the South Cove in colonial times, which was narrowed by fill beginning in the 1830s to create the Fort Point Channel. It has remained mostly vacant land since the late 1800s when the area was developed and expanded by fill dredged from the Boston Harbor. A sea wall was created on the east side of the Fort Point Channel in a curved fan shape, creating the so-called Fan Pier. In the 1960s, the Fan Pier was planned for development, but was postponed for financial reasons until the 1990s when the John Joseph Moakley U.S. Courthouse was built in 1998. A twenty-story Grand Hyatt Fan Pier is now planned to be across the street at 28-70 Old Northern Avenue. Both of these buildings are/will be supported on pre-cast concrete piles driven deep into the till. The South Boston Seaport district is currently undergoing a remarkable transformation in spite of relatively poor soil conditions that generally consist of fill over organic soils to depths of 6 to 9 meters (20 to 30 feet), followed by local outwash sand overlying the marine clay. The clay varies from 12 to 24 meters (40 to 80 feet) thickness, and often has a stiff over-consolidated crust. Below the clay is the lower outwash, then till, with argillite below. Other new buildings recently constructed include:

- The sixteen-story World Trade Center East on Seaport Avenue constructed in 2000 with a three-level below-grade garage and founded on a concrete mat on marine clay. World Trade Center West (built in 2002) with seventeen-story offices and three-level below-grade parking on World Trade Center Avenue and built on a concrete mat bearing on clay (Siebert, 2012).
- The Manulife U.S. Headquarters at 601 Congress Street constructed in 2004 consists of a fourteen-story tower with four levels of parking covering 80 percent of the above-grade footprint, 12 meters (40 feet) below grade and 9 meters (30 feet) below the water table. The southern portion of the building near the Silver Line bears on 1.2 meter (4 foot) diameter end-bearing shafts drilled into the argillite. The remainder of the building is supported on a 1.2 to 1.5 meter (4 to 5 foot) thick concrete mat floating on the marine clay with the perimeter slurry wall toed into the clay (Siebert, 2012).
- The twenty-two-story Renaissance Boston Hotel at 606 Congress Street was built three blocks from the waterfront between 2005 and 2008. The foundation consists of pre-stressed, pre-cast concrete piles that were driven to bedrock at 30 meters (100 feet). Because of the dense sand known to exist under the site, the piles were pre-augered to 18 meters (60 feet) (Wallace, 2012).
- The Fan Pier development consists of three buildings. One Marina Park Drive, an eighteen-story office building built in 2010, is supported by a 1.5 to 1.8 meter (5 to 6 foot) thick concrete mat bearing on the marine clay at a depth of 12 meters (40 feet). A portion of the building that is constructed in the area of the old ship channel is supported by caissons drilled into the clay to a depth of 21 meters (70 feet). The Vertex Pharmaceuticals buildings at 50 Northern Avenue and 11 Fan Pier Boulevard are constructed on a mat similar to caissons used on One Marina Park Drive at Fan Pier (Martini, 2012).
- The Boston Convention and Exhibition Center Complex at 415/425 Summer Street, completed in 2004, with the adjoining seventeen-story Westin Boston Waterfront Hotel that was constructed from 2006 to 2009. In this complex, the low-rise portion of the hotel is founded on 32.4 centimeter (12.75 inch) outside diameter concrete-filled pipe piles (wall thickness 0.95 centimeter [0.375 inch], with 934 kilonewton [105 ton] capacity). The piles were driven to end bearing in the till and the argillite. The high-rise portion of the hotel or tower is supported on a series of 0.9 to 1.8 meter (3 to 6 foot) diameter rock-socketed drilled caissons. The Convention Center is supported both by 35.5 by 35.5 centimeter (14 by 14 inch) pre-cast concrete piles driven to till and argillite and 1.2 to 2.1 meter (4 to 7 foot) diameter caissons drilled to the argillite for the larger loaded columns and to provide resistance to lateral loads (Siebert, 2012).
- The Seaport Hotel at 1 Seaport Lane consists of three buildings: the seventeen-story West Office Building (built in 2000), the seventeen-story East Office Building (built in 1998) and the fourteen-story Seaport hotel and tower (built in 1996). A three-level garage exists under all three buildings. Soils found at the site consist of up to 6 meters (20 feet) of both granular fill and dredged (in 1890) clay and organic silt from Boston Harbor. A 1.5 meter (5 foot) layer of organic silt and peat underlies the fill and in turn overlies a 3 to 4.5 meter (10 to 15 foot) thick layer of the upper outwash sand. A 21 to 33.5 meter (70 to 110 foot) thick layer of overconsoli-

dated marine clay that becomes softer with depth underlies the upper outwash. An intermittent layer of the lower outwash that reaches 12 meters (40 feet) in thickness was encountered below the clay. A 4.5 meter (15 foot) thick layer of till is then found overlying argillite of varying hardness and varying degree of weathering. The perimeter walls were sealed into the top of clay as a permanent groundwater cutoff wall and foundation. All three buildings bear on the marine clay at a depth of 12 to 14 meters (40 to 45 feet), with a bearing capacity of 240 kilopascals (2.5 tons per square foot). Long-term settlement was determined to be less than 2.5 centimeters (1 inch) using the underdrained mat foundation system (Erickson, 2012).

- The Park Lane Seaport 1 and 2 Project consists of two apartment buildings of thirteen and eighteen stories. It is located at One Park Lane and the buildings were constructed between 2004 and 2006. The shorter building is founded on a 1.5 to 1.8 meter (5 to 6 foot) thick concrete mat foundation on the marine clay at a depth of 12 meters (40 feet). The taller building is founded on steel H-piles driven to the till at a depth of 33.5 to 36.5 meters (110 to 120 feet) (Martini, 2012).

Alewife Station & Condominiums — Construction Issues. Usually there is very little trouble with constructing deep foundations or balanced mat foundations for tall and medium height buildings in the Boston area. However, at the Alewife Station on the MBTA Red Line in West Cambridge, the reworked, sensitive clay was found to cause serious problems. This quite different formation proved very problematic, both during construction in the 1980s and for possible future development.

Foundation problems were also encountered more than twenty years after Alewife Station construction during the construction of a nearby condominium complex (Roma, 2012). The planned foundation design consisted of PIFs to a depth of 15 meters (50 feet), where the expected sand of the outwash deposit above the marine clay at the base of the PIFs would be compacted. At this depth, however, a loose rounded sand and gravel was encountered that could not be compacted when the PIF base was driven out and expanded. According to the contractor, it was only the second time in their experience that such a condition had been encountered. Precast concrete piles were substituted and driven to the deeper till found at a depths of around 24 meters (80 feet). As described in Chute (1959), interbedded clays and silts underlie the area. This condition with the PIFs could have been caused by confined conditions from the interbedded sand and clay, or by saturated or supersaturated "running sands." The roundness of the sand and gravel where the fines are not now present because the fines might previously have been washed out could indicate that an ancient stream bed deposit was encountered.

Conclusions

The city of Boston is underlain by a complex mixture of both deformed and undeformed soils. The historical development of Boston in the early years was influenced by the geology that limited the heights of buildings in some areas. Compounding the complexity is the fact that the bedrock, mostly argillite, can be found at very shallow depths such as in the Government Center, the West End and Charles River Place, but within a short distance of 4 kilometers (2.6 miles), the rock plunges to depths greater than 76 meters (250 feet) in the Charles River area. The geology dictated the types of foundations for buildings that have been built. Each area of Boston has its own geological and geotechnical conditions that made use of a variety of foundation types. These types included belled and straight shaft caissons, pipe piles, wood piles, H-piles, pre-stressed concrete piles, footings and mats to the point that buildings at a particular street intersection could have four foundation types. The following geologic factors determine the choice of foundation type:

- The bedrock surface is highly variable.
- The argillite, and to some degree other bedrock, can be deeply kaolinized to the consistency of clay.

- The rock is deeply weathered in certain areas.
- The till and glaciomarine deposits may behave plastically, affecting the behavior of piles. The till can contain layers and lenses of sand and gravel that are water-bearing.
- Deformed, mostly faulted clay, sand and gravel and till are found in the area of Beacon Hill.
- The marine clay is thick and can be nearly normally overconsolidated. In certain areas, some of the clay is reworked and is sensitive, with loss of strength.
- The upper and lower outwash deposits are discontinuous and sometimes absent. Where present of sufficient thickness, PIFs can be used.
- The original wood pile foundations are susceptible to deterioration when the water table is lowered.
- Overlying organic silt has softened the normally stiff yellow clay crust.