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GEOTECHNICS OF FAMOUS STRUCTURES

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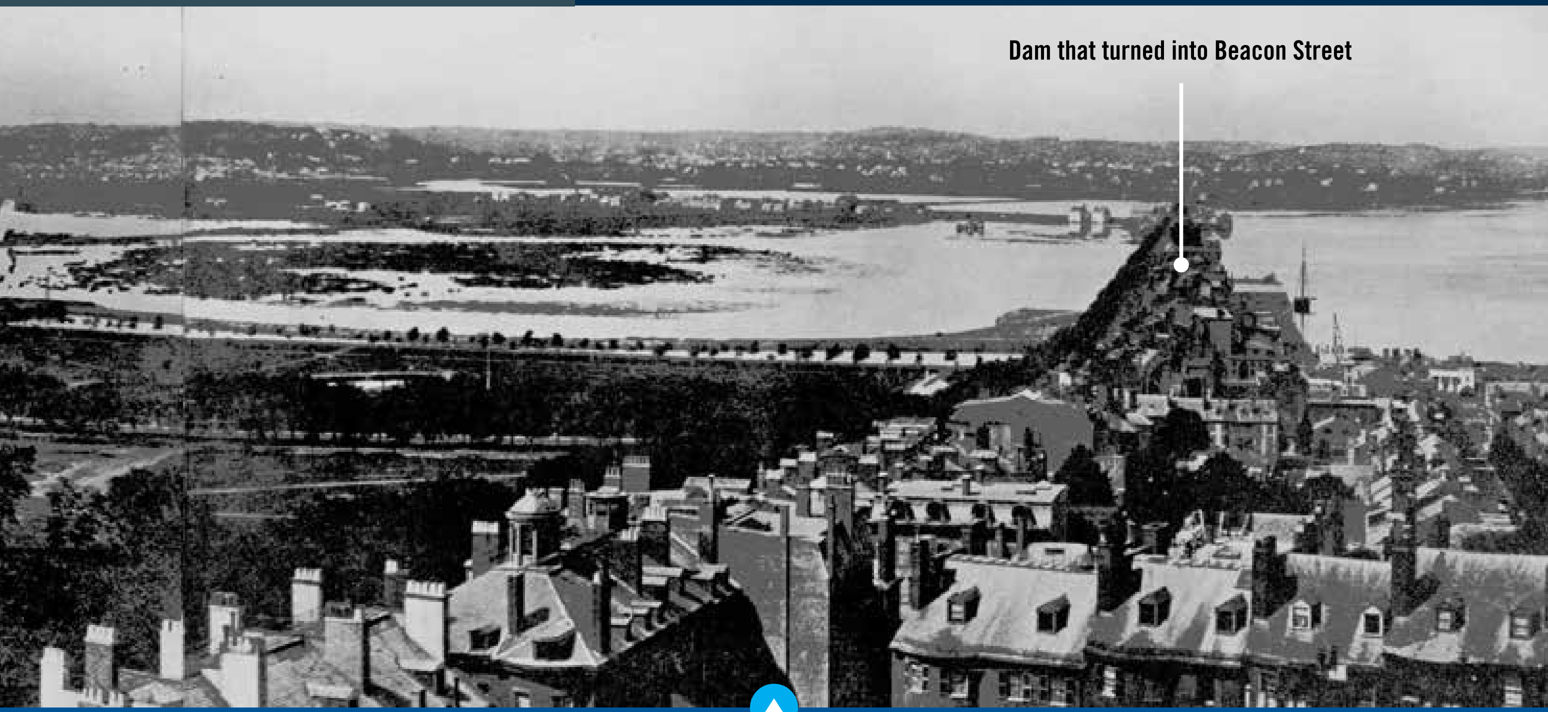
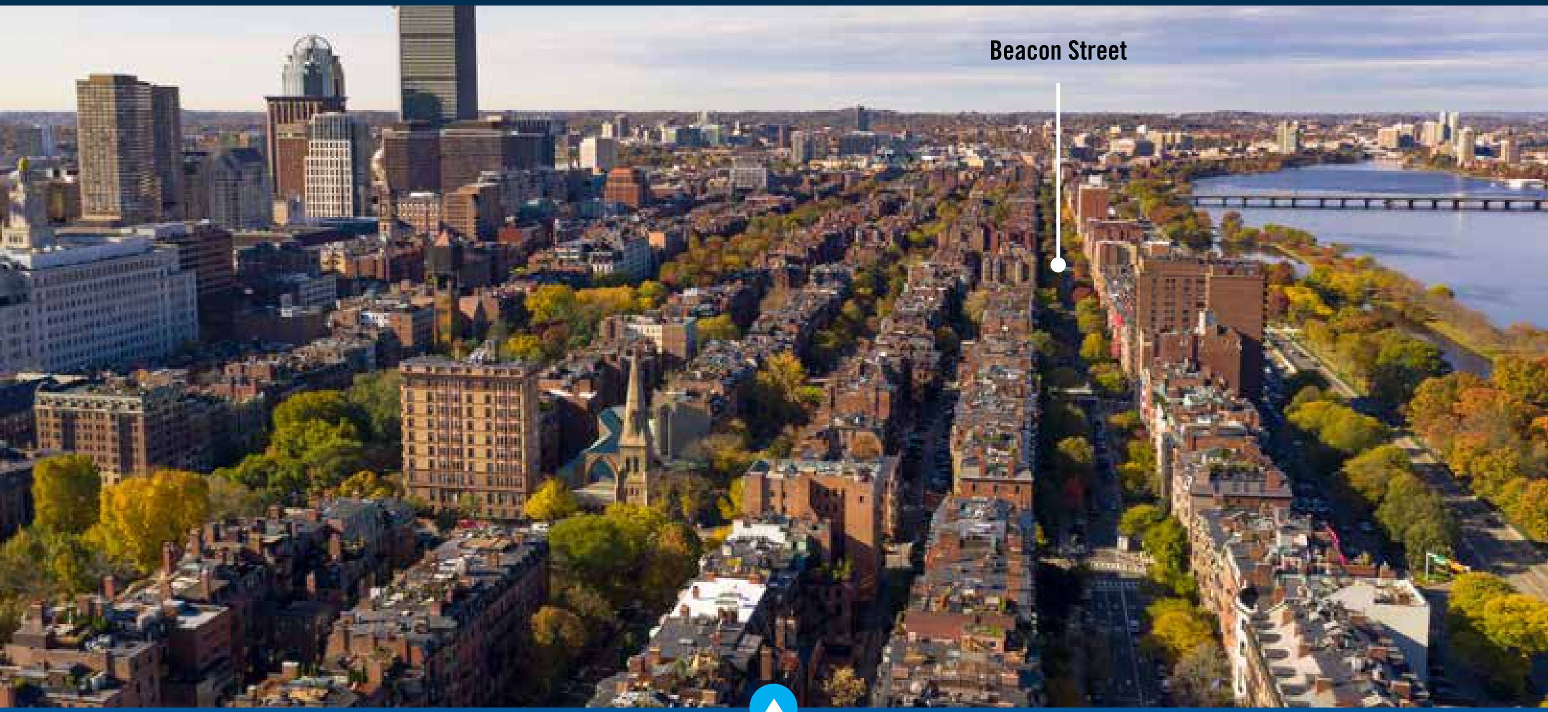


Boston Public Library

1857

WHAT LURKS



PRESENT DAY

The Geotechnical Intrigue of Boston's Back Bay

By Jim Lambrechts, PE, M.ASCE

BELOW

In 1858, the great filling of Back Bay began. Completed in about 20 years, it led to nearly 100 city blocks of iconic 4- and 5-story brick rowhouses. In the past 60 years, about 50 high-rise buildings have sprouted along the "spine" of Back Bay. No matter the size, all have had to accommodate the geotechnical intrigue of Boston's Back Bay.

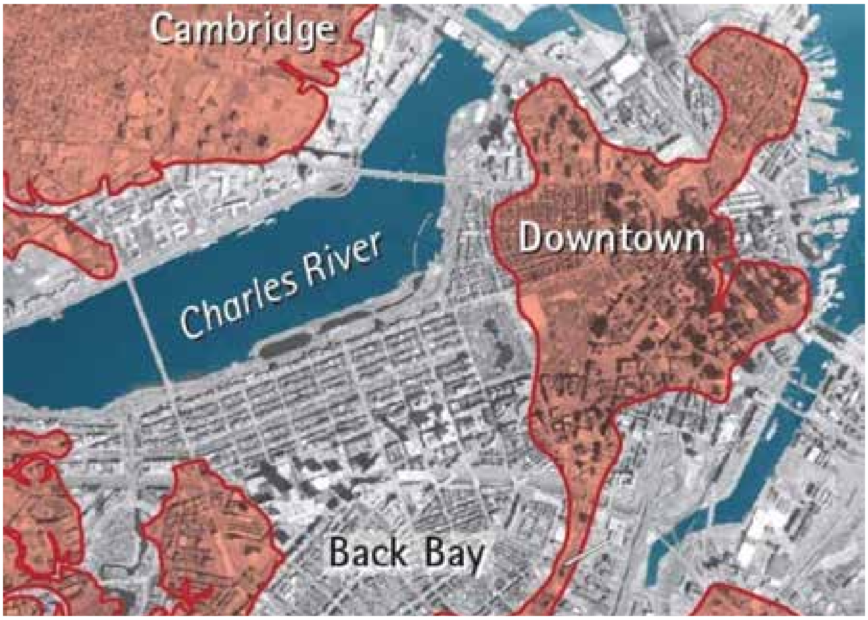


Figure 1. **Colonial Boston was small, surrounded by water. (Courtesy of Weiskel, Lora, and Smieszek, USGS Circular 1280, 2005.)**

The more than 700 people who set sail from England in 1630 to found Boston had no idea that their choice of location would be so influenced by geologic events that began nearly 600 million years earlier. Back then, a long, rather narrow volcanic island was depositing sediments in a long trough off the coast of present-day northwest Africa, when both were near the South Pole. The settlers were simply in search of a new land that would provide the essentials: fresh water, a workable harbor, and land that was defensible against invaders. The hills and unique geologic setting of Boston offered all three. When Boston was founded, Back Bay was no more than a swamp, mostly underwater at high tide (Figure 1). Two hundred years later, however, the Back Bay would have a great deal to do with the continuation of Boston as the major city in Massachusetts.

Bedrock Origin – Making the Boston Basin

Stepping back in time about 600 million years, sediments were being eroded from the mountains of a more than 600-mile-long volcanic island. These sediments would turn into the Roxbury Conglomerate (coarse sediments left largely above water) and the Cambridge Argillite (finer sediments deposited underwater) of today's Boston Basin. Plate tectonics then moved the island across the vast ocean to collide with the continent called Laurentia, the core of North America. Together, these units formed the bedrock of eastern Massachusetts and elsewhere. Through tectonic movement processes, igneous intrusions have occurred — some as massive volcanoes and granite batholiths, and others as narrow basalt dikes pushing through the already existing bedrock.

Boston's present-day bedrock surface reflects the resistant nature of the granite and metamorphic rocks that surround the Boston Basin. The conglomerate is also fairly strong, and stands prominently as hills next to its lifelong neighbor, the more readily erodible argillite, which has seen valleys eroded to depths of more than 200 ft. It's the presence of this easily weathered and erodible argillite that has given Boston and the Back Bay its geotechnical intrigue.

Glaciers and Boston Blue Clay

Nature's great bulldozer essentially scraped the New England bedrock landscape bare within the last two million years, and provided a new layering of soils for our geotechnical amusement. Over a period of about 3,000 years, the glacial till, outwash, rock-flour sediments (i.e., blue clay), more outwash, lacustrine, and alluvium were deposited. Glacial filling in Boston began about 14,500 years ago, with a later episode of glacial re-advance that bulldozed up hills of the original peninsula and provided fresh-water-bearing strata to attract the colonists of 1630.

Blue clay was deposited in a marine environment, filling the deep valleys previously carved into the soft argillite by streams and further deepened by the glaciers. In some areas in and around the Back Bay, the clay is nearly 200 ft thick, but it's more usual thickness is in the 50-80 ft range.

Owing to its marine deposition, numerous small shells are often found in samples of the clay. It's not unusual to find a cobble or boulder embedded somewhere in it, a remnant stone dropped from ice rafting. On one occasion early in my career, it appeared that a glacial till high had been discovered when, after about 60 ft of blue clay, a 10- to 20-ft thickness of dense glacial till was encountered in a number of preliminary test borings over more than a 2-block-long area. Upon drilling the design-phase borings, another 10 to 20 ft of blue clay was discovered below this upper "fake" till. The hoped-for "shorter" piles then had to become exceptionally long to reach firm end bearing on the real till or bedrock.

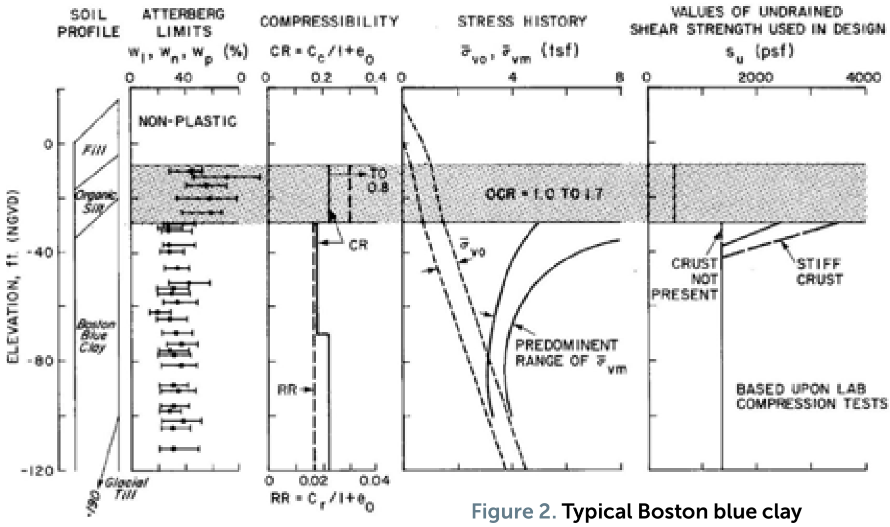


Figure 2. **Typical Boston blue clay properties across Back Bay.**

Boston's blue clay was exposed to air when glacial re-advance again lowered sea level. Weathering, desiccation, and freeze-drying caused the blue clay to develop a stiff, yellow crust in the top 5 to 10 ft, with OCR values of 5 to 10 and N-values commonly greater than 20 blows/ft. N-values decrease with depth, and 40 to 60 ft into the clay, single digit to WOR N-values are typical. Consolidation tests show the precipitous decline in maximum past pressure, such as those shown in Figure 2 from tests made along a mile-long length of a subway alignment across part of Back Bay. But throughout its depth, some minor overconsolidation is present in the blue clay; how much is part of the geotechnical intrigue.

Making Land in the Back Bay

By 1800, Bostonians recognized they needed more land. As ships required deeper anchorage berths, harbor front was filled, and longer wharfs were constructed with soil taken from the hills. The 1630s Mill Pond was filled in because silt had accumulated, rendering it no longer effective in harnessing tidal power. However, developers saw a chance to make a new tidal pond west of the Boston peninsula by enclosing the Back Bay and part of the Charles River estuary. By 1821, the tidal Back Bay was harnessed to become a huge Mill Pond system as seen in the 1857 photo on the first page of this article. The mile-long, 50-ft-wide earth fill dam with granite block walls eventually became today's Beacon Street.

By the mid-1830s, the Mill Pond system was obsolete with the advent of steam power. The new railroads entering Boston necessitated that engineers construct long embankments that created isolated lagoons; these became stagnant and then polluted with sewer outfalls and waste dumping. The need to expand Boston's land area and eliminate the lagoons led to a massive, 30-year-long land-filling project that would create the area now known as Boston's Back Bay and the adjacent Fenway area.

Granular fill was imported from glacial hills more than 9 miles away by three, 35-car trains, sometimes working around the clock. Steam shovels loaded the trains from the sand and gravel hills, and then the train cars were side-dumped to unload the fill over the mud flats. Horse-drawn spreaders then distributed the fill. A regular planned grid of streets was filled up 5 ft higher than house building lots. The 10- to 20-ft thickness of fill caused as much as 3 ft of compression of the organic silt stratum over the following two decades, along with some compression of the blue clay. Some secondary compression continues today, at about 1 in. every 20 to 40 years.

Early Foundations – Only One "Game" in Town

Building development quickly followed the filling, as illustrated in Figure 3. Four- to five-story-tall brick rowhouses were constructed on wood pile foundations driven by drop hammer 25 to 40 ft through the new fill and organic silt strata to substantial end resistance on the stiff clay crust or outwash sand above the blue clay. Granite blocks were used as pile caps, which limited pile spacing. Timber piles were used to support more than 2,000 buildings constructed throughout Back Bay in its first 30 years. Under the famous Trinity Church in Copley Square, 700 wood piles were reportedly used to support each of the church's four massive stone pillars, with about 4,500 piles required for the entire church.

Engineers knew that to keep wood piles preserved, their tops had to be submerged. Top-of-pile elevation was generally slightly below mean sea level, or at about the average level of the then-tidal Charles River.

Figure 3. **Development quickly followed Back Bay land filling. (From the collection of Edmund Johnson of Haley & Aldrich, received 1995.)**

In 1929, while investigating the cause of cracking and settlement of the Boston Public Library building in Copley Square, severely rotted tops of wood piles were found in fill that was no longer saturated. One-third of the massive library needed the tops of its wood piles repaired.

In the 1980s, 21 contiguous rowhouses at the edge of Back Bay near the Charles River were found to have rotted wood pile tops, and the issue of lowered groundwater again made headlines. The cause was eventually determined to be a change in the manner of operation of a nearby 8-ft-diameter combined sewer overflow (CSO) collection conduit that had been made necessary by the construction of the new Charles River Dam over a half-mile away. Today's Boston Groundwater Trust is a result of the 1980s problems, with an active program to monitor and report groundwater levels in over 800 observation wells, and to actively pursue remedy when low groundwater levels occur. Old, leaking sewers are often found to be the cause, and the Boston Water and Sewer Commission aggressively acts to find the leaks and implement repairs. More geotechnical intrigue.

A Wide Choice of Foundations over the Past Century

The use of concrete and steel for foundations at the turn of the last century opened a new window on foundation design and construction. The single focus on wood piles ended, although wood pile use continued into the later 20th century. The wide variety of different foundations used in Back Bay is illustrated in Figure 4.

Hand-dug caissons were adopted early on, with 3-ft-diameter shafts and expanded belled bases to make use of higher bearing capacity afforded by the crust of Boston's blue clay. Concrete frame buildings of 10- to 12-stories were constructed using such foundation systems with 4 to 5 ton/ft^2 allowable bearing pressures supporting 6- to 8-ft-diameter caisson bells. Eventually, machines took over the bulk of the drilling process, but "sand hog" workers still had to manually clean the bearing surface for the geotechnical field representative to inspect and verify clay bearing capacity.

The "floating" foundation came about in the 1930s with the construction of the 12-story New England Mutual Life building, which had a basement excavation depth great enough to relieve the clay of a load greater than the new building would apply. This foundation was a triumph for modern soil mechanics, with significant involvement by Arthur Casagrande.

In 1929, while investigating the cause of cracking and settlement of the Boston Public Library building in Copley Square, severely rotted tops of wood piles were found in fill that was no longer saturated. One-third of the massive library needed the tops of its wood piles repaired. A major inquiry determined the cause of groundwater lowering to be leaks into the St. James Avenue sewer, because groundwater levels quickly rose when it was plugged and filled. In response, more than 700 observation wells were installed in the 1930s throughout Back Bay and other filled-land areas of Boston, and monitored through 1940 to determine groundwater levels. Unfortunately, no records exist as to the actions taken when or where groundwater was found to be below commonly used top of pile El. 5, and the program's funding from the depression-era Works Progress Administration (WPA) ended.

The 30-story Hancock Clarendon Building was built in 1946. The first true "high-rise" in Back Bay, it is notable today for its lighted mast, which indicates approaching weather. Here was the first use of deep end-bearing steel H-piles, driven to glacial till or argillite bedrock. Just 14 years later, redevelopment of a huge railroad yard in the middle of Back Bay began to produce the now iconic Prudential Center. A variety of foundation systems was used. The 52-story main tower is founded on 30-in.-diameter, concrete-filled shafts drilled to a depth of 200 ft to penetrate 30 ft into the argillite bedrock. Other foundation types used for Prudential Center buildings have included deep concrete filled-pipe piles, precast-concrete piles, and drilled shafts. Pressure injected footings (PIFs) and wood piles extend to the outwash sand above the blue clay to support lightly loaded stores and the two-level parking garage. Recent buildings constructed at the "Pru" have used high-capacity drilled micropiles penetrating into the deep bedrock and a floating foundation.

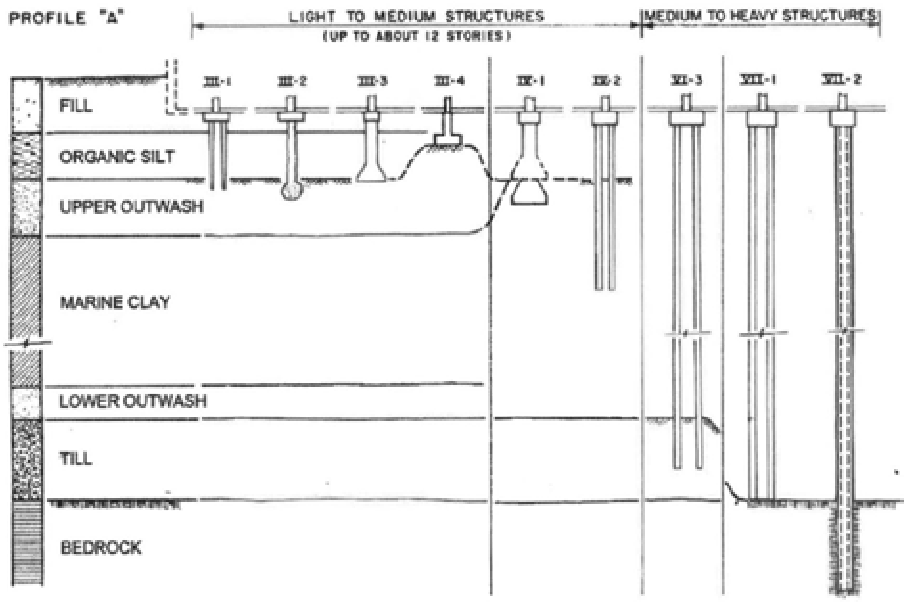


Figure 4. **Deep foundations used throughout the decades. (Courtesy of Woodhouse and Barosh, Civil Engineering Practice, *Journal of the Boston Society of Civil Engineers*, 2011-12.)**

A number of buildings were developed in the late 1960s to early 1970s at the nearby Christian Science Center (CSC), with most having PIFs to the upper outwash sand, which were the foundation of choice for buildings of intermediate height at that time. Geotechnical engineers usually try to provide the client with the most economical solution that will give the desired performance, while contractors sometimes offer cheaper alternatives. Such was the case of the parking garage and overlying reflecting pool at CSC, where deep end-bearing piles were supplanted with short PIFs, at substantial cost savings. But the architects' desire for water to spill uniformly over all sides of the nearly 700-ft-long reflecting pool were not realized due to very slight, uneven settlement, or perhaps heave of the underlying the blue clay — part of the geotechnical intrigue of Boston's Back Bay.

The John Hancock Tower's construction in the 1960s is another part of the geotechnical lore of Back Bay. To achieve the deep, two-level basement, steel-sheet piling supported by wales and rakers to a central concrete base slab on end-bearing steel H-piles needed intermediate temporary lateral support from a berm of fill and organic silt. But although the organic silt can exhibit a drained friction angle of about 30°, it behaves as very weak clay when undrained. The sheet piling deflected inward 2 to 4 ft, which led the surrounding ground to follow and settle. The adjacent streets and buildings suffered, including Trinity Church, more than 50 ft away and across St. James Avenue.

Imagine the angst at Trinity Church when, just 15 years later, another development with a 32-ft-deep excavation was proposed just across its other abutting street. But this time, a stiff concrete slurry wall with several levels of tiebacks was used, and extensive monitoring confirmed tolerable lateral movements (just 1-3 in.). The deep excavation also allowed this 30-story building to "float," although some auger-cast concrete piles with steel cores were needed for hydrostatic uplift and wind load overturning resistance.

There's Always Geotechnical Intrigue in Back Bay

What type of foundation is needed for a project in Back Bay does not elicit a simple answer. Many factors enter into the solution. A significant factor in the past three decades has been the possible presence of environmental contamination in the fill. What local industries might have been present over the past 160 years? A tannery? A glass manufacturer? A manufactured gas plant, with coal-tar residue still present? Wood and coal ashes were just dumped out back, but these often contain heavy metal residue. It may be more economical to forego the basement excavation and just drive deep end-bearing piles for a rather short building (4-6 stories), rather than remove the contaminated fill. But three blocks away, a 22-story building over even-deeper blue clay happily "floats" on a thick, concrete mat placed 20+ ft below ground, contamination removal costs being less than deep foundation installation. What new problems will the next decades bring? Such is the fascinating geotechnical intrigue of what lurks below Boston's Back Bay.

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