AC 2008-1977: THE PROBLEM OF GROUNDWATER AND WOOD PILES IN BOSTON, AN UNENDING NEED FOR VIGILANT SURVEILLANCE

James Lambrechts, Wentworth Institute of Technology

The Problem of Groundwater and Wood Piles in Boston
"An Unending Need for Vigilant Surveillance"

Abstract

The stately rowhouse buildings in many areas of Boston were founded on wood piles in the 1800s. Preservation of wood pile foundations requires that groundwater levels remain high enough to inundate the tops of wood pile foundations. This has become a major problem in some areas of the Back Bay, the South End and Fenway neighborhoods of Boston. Costs for wood pile repair in the last 25 years totals more than $20 million. Old infrastructure and impervious surfaces are primary sources that have been identified as leading to lowering of groundwater. City government has established the Boston Groundwater Trust to measure and report groundwater levels, which now uses a network of 800 observation wells. However, the elevation of wood pile tops is not reliably known. Research is underway to investigate possible use of remote sensing methods. Recharging is also being required at new developments and major renovations, but more recharging needs to be done by individual property owners as well. A program to aggressively search for the causes of lowered groundwater and make necessary repairs to infrastructure and building basements is underway. Much of the 'leg-work' has been done by co-op students from the Wentworth civil engineering technology program, who have searched for observation wells, monitored observation well installations, measured water levels in wells eight times a year, investigated recharge systems to replenish groundwater, made numerous grain size tests on fill samples and most recently designed an alternative and far less expensive 'foundation replacement' system. The groundwater and wood pile problems are unique in their extent throughout Boston's filled land areas, which leaves us with a never-ending need for vigilant surveillance in the struggle to preserve these vital foundations for thousands of rowhouse buildings.

Introduction

In Boston, there are many thousands of rowhouse residences that are founded on wood piles. The information presented herein provides an overview of the problems of groundwater and wood piles and the struggle to preserve these vital foundations for many thousands of buildings in the filled land areas of Boston. Several issues related to the preservation of wood pile foundations are discussed with particular reference to the work of a number of students from Wentworth Institute of Technology over the past decade both on their co-op work semesters, as senior design projects, and as special topics study. Their efforts have included observation well readings, research for wood pile top elevations, details on fill soil composition and location, study into restoration and preservation of groundwater levels to heights above pile tops sufficient to maintain the structural integrity of the piles, and design of alternative means of building support. In such context, background on the geologic origins of the ground beneath the Filled Land areas is reviewed, as are the "much more recent" events that have impacted groundwater and wood pile integrity.

Regarding groundwater levels, the continuing program to measure groundwater levels in 840 observations wells and uses of the data are discussed. Two different efforts are required for maintaining groundwater to preserve the wood piles that are still intact, namely stopping withdrawals and recharging to add water to the ground have also been subjects of student research. Methods for repairing wood piles that have suffered decay, or for installing separate mat-slab foundations have also been topic of student research.

The major problem with wood piles occurs when groundwater levels drop and expose the wood at the top of the pile to air, which will trigger spores of fungi that are naturally in the wood to produce the wood rotting organisms. Once started, the fungi will slowly and steadily work through the wood cell structure and cause the wood to progressively weaken, eventually to the point where there is not enough sound wood left to support building loads. The rotting seen most often works its way from the perimeter in towards the center of the wood pile. In some instances it may take only a few years for most of the pile top to rot away, but in other cases it may take a few decades, and the rate will often vary from pile to pile (or from tree to tree). Figure 1 illustrates the damage that can occur, with one pile being substantially decayed to the consistency of peat moss over its top two feet, and the other having lost all but 1 inch of its top diameter to rot (the horizontal 'pegs' show where the tree branches were, and illustrate the original diameter of the tree/wood pile).

Unfortunately, the first evidence of improper support usually occurs as cracking in plaster walls or in the exterior brick masonry. When this type of damage is observed, there has already been substantial settlement, which has occurred because there is no longer adequate support at the tops of the wood piles to carry building loads. But even though it is too late to preserve the integrity of the wood pile tops, there will still be good wood a foot or two lower that will not have rotted and upon which the house can be resupported, provided that wood remains submerged. Therefore, constant vigilance is needed to maintain the groundwater above wood pile top elevations to prevent rotting from beginning, and to keep rotting from going deeper.

The Boston Groundwater Trust was formed by the Mayor of Boston in 1986 with the charge to determine groundwater levels and to report the data, which it does quite effectively. Since the Boston Groundwater Trust began to receive funding in 1999, Wentworth Co-op students have been employed for making field readings, specific research, and special design development. A summary of the numerous activities undertaken by the Wentworth students over the past 10 years is presented in Table I. Many of these efforts are further discussed under appropriate topic categories later in this paper.

The extensive data developed by the efforts of the co-op students and its subsequent analysis and summary by the Boston Groundwater Trust and other civic organizations have led to attention being taken by public agencies officials who now have groundwater preservation as a high priority. Not only do withdrawal sources to leaky infrastructure have to be found and repaired, but methods to replenish groundwater must also become a vital public effort because stopping the withdrawals of groundwater will not be totally effective. There needs to be more water introduced into the ground to replenish the aquifer to levels that will again submerge the exposed wood piles and keep all others safely below groundwater level. This effort continues to be the subject of student research and development on both the mechanics of solutions and environmental issues of urban recharge that will both remove precipitation from the wastewater stream and aid the preservation of wood pile foundations.

Background and Setting

Geology has had a major influence on the founding and development of numerous cities in the U.S., but probably nowhere has it been as profound as in Boston. To this day, and well into the future, geology controls not only the building of new structures but also the preservation of thousands of existing structures. It is not just geology alone; our forebearers added to what the natural geologic processes had given the early settlers by undertaking great land-making operations, primarily in the 1800s and early 1900s. For example, Figure 2 shows the outline of the original colonial shoreline of the Boston peninsula relative to the present day city, a process in which there were numerous episodes filling[1]. It is the areas of made-ground that are the focus of the research and study reported herein. The conclusion reached is that today and into the next centuries, we must live with the ground conditions present, and continue to preserve and "defend" the foundations which support a substantial part of our great city. The following summary of the geology of Boston comes from a number of references, but excellent overviews are in works by Skehan [2], Barosh, Kaye and Woodhouse [3], and Newman and Holton [4].

Geologic Origins of the Boston Peninsula - The origins of the ground of Boston date back to about 600 million years, when the bedrock of the Boston area was first being formed. A down-faulting of massive blocks of the bedrock allowed for the accumulation of new sediments in what we today call the Boston Basin. These sediments eventually turned into the rock formations we call the Cambridge Argillite and Roxbury Conglomerate. The argillite (slightly metamorphosed shale) is more easily weathered and eroded than the harder igneous rocks that surround the Boston Basin. Therefore, the top of the softer argillite bedrock is today substantially lower. It may be that this bedrock was never up to the same elevation as the granitic highlands that lie a short distance to the west, south and north. What was the local topography before the glaciers of previous ice ages ? No one can say for sure, but we can say that the glaciers would have had an easier time gouging out the softer argillite bedrock of the Boston Basin to even greater depth than the conglomerate or the granitic rock of the surrounding areas. In some places the glacial ice sheet did not scour all the soil from the landscape and landforms we call drumlins were left behind (such as in many islands in the inner Boston Harbor). Some hills in Boston are also drumlins.

Upon its retreat from forming Cape Cod and the Islands, the last continental glacial ice sheet to cover New England left behind a variety of interesting soil formations. The deeply gouged Back Bay was an ideal location for developing thick marine sediments, today known as the Boston blue clay. At some time, the surface of this marine sediment was exposed to air as worldwide sea level was lowered during glacial readvance. This exposure resulted in the upper portions of the clay becoming hardened (either by freezing, drying out or both).

The geologists tell us that after the major retreat of the glacial ice sheet, "smaller" glaciers revisited Boston and these pushed up hills, such as the original colonial Boston peninsula, including Beacon Hill. Perhaps some glaciers also built upon drumlins that were already in place. These high hills of the Boston peninsula would then form the base for the founding of the city in the early 1600s. Finally, as the small glaciers were bidding a last farewell on their final departure, their glacial meltwaters caused localized sand and gravel deposits to form as outwash deposits from the heavy stream and broad areas-wide out washing of the glacial meltwaters. The area across Back Bay from the original Boston peninsula known as Gravelly Point was formed by such outwashing. The difference in resulting subsurface soils between the Boston peninsula and the Back Bay is illustrated in geologic cross-sections by Kaye [5] shown on Figure 3. And perhaps the glaciers knew there would be need for making more ground, so other plentiful sand and gravel deposits were left not too far away in the valley of the Charles River for man to use to expand the peninsula a few millennia later.

The last of the local soil deposits were 'home-grown'. As worldwide sea level rose with the melting of the glaciers, the mass of bedrock underlying New England also reacted to the departure of the ice age glaciers by rising up. A balance was finally reached in this area. The sea level came to equilibrium with the land of Boston and has been within a couple of feet of this relative level over the past 2000 years.

In the 8,000 years time between the glaciers leaving Boston and the stabilizing of sea level here, wide expanses of salt marshes developed. These salt marshes would have been much like we see today behind the dunes along the New Hampshire coast. In the Boston Basin, particularly the area behind the Shawmut peninsula, the former salt marshes were eventually inundated by rising sea level, and the colonists simply found tidally exposed mud flats in the Back Bay area. But in other areas and around the perimeter of uplands, other swamps and salt marshes were certainly present in the colonial times and into the late 1800s.

Man-Made Ground - The stories of modern-day "ground making" are marvelously described by Seasholes[1]. The result of the placing of fill over the soft mud deposits to make ground for development has however left a legacy that we must protect. This legacy is the wood pile foundation, upon which most structures in the filled land areas were founded. The use of wood piles was 'state-of-the-practice' for deep foundation construction in the 1800s. Many of buildings of the original campus of M.I.T. built just across the Charles River from Boston in the second decade of the 20th century were also founded on wood piles.

The fill that was placed to expand on the perimeter of the original Shawmut peninsula was at first derived from nearby hills of the peninsula. Early earthmoving was done by hand and horse, picks, shovels and horse carts. The composition of the fill reflects its source. Glacial till that blanketed some portions of the Boston peninsula is composed of a wide range of soil types, and is considered "well graded". It is most often predominantly sand, but with goodly portions of gravel and fines (silt and clay). Outwash deposits on the other hand are almost entirely sand, with localized gravelly zones. And soil dredged up from the tidal mud flats would be mostly silt, but may also include some fine sand and clays. In most cases the muds contain some amounts of organic matter.

The massive filling of the Back Bay and Fenway used mostly sand and gravel imported from kame terrace hills and esker deposits eight to ten miles away in Needham and Canton (for much of the Back Bay filling), and similar hills in Auburndale and Weston for areas of Fenway. For the most part the fill was simply dumped onto the mud flats, with no specific compaction, so it was of relatively loose consistency. Except where there have been excavations and major construction, the fill of the past centuries would be expected to still exist in much the same condition as when placed. This is a condition that invites another area of research and design related to liquefaction potential and its mitigation.

Wood Pile Foundations and Groundwater

As noted above, the wood pile foundation was the "state of the practice" in deep foundation construction in the 1800s. Neither steel nor concrete were yet available, and wood piles had been used for foundations of structures for several thousand years. Of course no one would install wood piles if they were not needed, but when the building site is underlain by soft soils, and the new structure will be heavy, then there is need for a firm foundation. The *term* favored is *wood piles* rather than timber piles because the piles were simply the trees and were not cut down to specific dimensions as is done in making timbers for wooden structural elements.

In foundation engineering and construction, the pile foundation is used to carry the load of a structure down through soft ground to a firm bearing layer. In Boston for structures of the 1800s, this bearing layer for support of wood piles exists within 25 to 40 ft of ground surface, as illustrated in Figure 4. The hard crust of the Boston blue clay or the outwash sand deposit that overlies the clay in some areas both provided sufficient load support for buildings constructed in the 1800s and early 1900s. The loose placed fill deposited over the very soft mud deposits was surely not adequate for building support. Wood piles are simply trees, stripped of their limbs and turned upside down, and driven into the ground with a falling weight (perhaps a one or two ton block raised up 3 to 6 ft and then allowed to drop free-fall on the bottom of the tree that was now standing upright).

Driving a wood pile was continued until the rate of penetration slowed considerably, indicating that the tip of the pile had encountered something hard, like the hard crust of the Boston blue clay or the sand of the outwash, either one of which would have offered far greater resistance to pile penetration than the very soft salt marsh muds or fill. After a few more drops of the driving weight to 'seat' the pile into the bearing stratum, driving would be halted. In many cases, the part of the tree remaining would be enough for a second wood pile to be obtained. So the pile driving rig would be moved over and the next wood pile driven at another required pile support location. The tops of wood piles were still sticking out of the ground a bit and these were not yet level. However, soon after driving, the tops would all be cut-off at the same elevation and made level for the placing of the granite block pile cap blocks.

The piles were spaced so that the granite blocks, then used for pile cap blocks, could adequately span over the tops of two piles. Pairs of wood piles would be installed along the location of each proposed wall of the rowhouse to be constructed. The typical arrangement of wood piles along the walls of rowhouses is illustrated on Figure 5. On top of these pile cap blocks, a second row of granite blocks was then used as the base of the building walls, with these blocks being turned 90 degrees from the underlying pile caps. The spacing between pairs of wood piles was dictated by the size of granite blocks available for the construction, which were generally 15 to 18 inches in cross-section (width and height) and 2.5 to 3 ft long. Figure 6 illustrates the arrangement of piles, granite block pile caps, and granite block wall blocks, upon which the brick walls of a rowhouse building would be constructed. In some areas of town, granite blocks were not used, but instead large chunks of the conglomerate bedrock, 6 to 12 inches in dimension, were stacked up above the tops of the pairs of wood piles to form pile caps and wall base. The conglomerate was readily available from outcrops in the nearby Roxbury neighborhood. As the granite blocks or conglomerate stone chunks were set in place, fill was shoveled in to surround the foundation caps and wall blocks. Two or three layers of granite blocks for wall bases were used before beginning the brick walls for the house, essentially bringing the stones up to about Elev. 12 (BCB) which was the level of fill placement throughout the house lots. Elevation reference is to Boston City Base datum (BCB), which is mean low tide level. The fill was placed up to El. 17 for the streets, generally 5 ft. higher than the house lots, which were laid out on the regular grid pattern.

At what level were the wood pile tops cut-off, and on what basis? These questions remain unanswered today. There was no specific regulation for elevation of wood pile tops. However, it was well known that the pile tops had to be kept submerged below groundwater for the preservation of the wood. It is unusual to find tops of wood piles much below Elev. +5 BCB. This level is about halfway between the mean high tide and mean low tide for Boston Harbor, which experiences about a 10 ft tidal variation twice a day. Occasionally, a somewhat higher cut-off grade was used, at Elev. 6 or Elev. 7 BCB. It is thought that the groundwater level would have been somewhat higher than mean tide level (by 2 to 4 feet) because there was little or no covering over the ground to prevent rainfall from infiltrating and the flow of groundwater would have been only toward the adjacent open bodies of water (the Charles River or Boston Harbor).

It was at one time widely believed that the predominate level for wood pile cut-off was El. 5 in the Back Bay, mostly due to statements made by Bunting [6]. However, over the past 40 years, a substantial number of the several hundred houses investigated have been found to have different levels, and mostly these have been one or two feet higher. This higher level has predominated in the lower Beacon Hill area, where wood pile cut-off grades have been found to be predominantly between Elev. 6 and 7 BCB [7]. Also, it has been found that there can be two or three different pile top cut-off levels beneath a single rowhouse! Suffice it to say that the level used for pile top cut-off would have been below the groundwater level at the time of original building construction. Unfortunately, records for levels used for top of pile grades through the later mid-1800s have largely disappeared over time. Today, there is only reliable reference data on top of pile levels for less than 3% of the several thousand houses in Back Bay, Fenway and South End neighborhoods. Some records for late 1800s into early 1900s have been found by Boston Groundwater Trust Co-op student researchers, who have in some winter semesters when it has been too snowy to read the observation wells, diligently pored through the 143 *volumes* of "Boston City Building Inspector Reports" (this represents the 3% findings).

Groundwater Levels

As noted above, the natural groundwater level should be expected to be above the level of surrounding water bodies, barring any 'outside' influences. The Charles River is now maintained as a controlled basin with water at Elev. 7.5 to 8 BCB, so there is no 'natural' reason for the groundwater in Back Bay, South End and Fenway to be lower. For reference, ground surface throughout most of Back Bay is Elev. 16 to 17, except for the "hill" that rises up around old Gravelly Point, which separated Back Bay from Fenway generally following along

Massachusetts Avenue. So groundwater should be about 8 ft. below ground surface. Unfortunately, groundwater is today several feet lower.

The groundwater level of interest to the preservation of wood piles is that in the Fill stratum. There are two other separate aquifers besides the Fill [8]. These are in the Outwash stratum that occurs in a goodly portion of Back Bay and Fenway between the Organic Silt and the Boston blue clay, and the deep glacial till that occurs at substantial depth below the Boston blue clay. In some areas, the Fill overlaps the Outwash aquifer directly, so the two groundwater regimes comingle. Such overlapping of the strata can be seen in the soil cross-section of the Back Bay shown in Figure 3. Because the Outwash sand stratum is in most areas isolated from direct recharge that is provided by precipitation infiltration, withdrawals from it by leaky infrastructure and basements can have great effect on lowering groundwater levels. It is usually found that the groundwater level in the Outwash is 2 ft. to 4 ft. lower than that in the Fill. The extent of the Outwash that was inferred by Cotton and Delaney [9] and modified by Aldrich and Lambrechts [8] is presented in Figure 7.

Also shown on Figure 7 is a summary of the available historical data in the 1930s regarding groundwater levels measured between 1936 and 1940 as part of the depression era Works Progress Administration (WPA) groundwater level monitoring project. Unfortunately, the bulk of the data from the WPA study were lost and only the highest and lowest levels in each observation well over the 4 year period are known for each of the 700 observation wells. As shown, only in a few locations were groundwater levels always below Elev. 5 (see dark and hatched areas on the figure). In most other areas, the groundwater was at some time found to be below Elev. 5 (light shading areas).

Concerns for groundwater levels and wood pile preservation have been on the minds of local engineers since the 1880s. In Stearns's report of 1894 for the planning of the Charles River Dam[10], it was noted that groundwater levels in 1878 and 1885, which are before and one year after construction of the Boston Main Drainage sewer system, were about the same and groundwater levels were between Elev. 6.7 and 8.5. However, he noted that observation wells installed in the 1890s, for a study of the proposed Charles River dam showed some local areas having groundwater levels below Elev. 5, and he proposed these were caused by leaky sewers with relatively localized influence. Further concerns were expressed in a 1914 discussion to a paper by Worcester[11].

It was the finding of rotted wood piles beneath the Boston Public Library in 1929, and concerns for the wood piles across the street at Trinity Church that set in motion the major 1930's study and the early public awareness of the tenuous relationship between groundwater and wood pile preservation[12]. But the issue lost advocates and public awareness with the onset of World War II, and the urban decline of the 1950s and 1960s. It was not until 1984 when rotted wood piles were discovered beneath the 19 contiguous rowhouses on the waterside of Brimmer Street in lower Beacon Hill that the issue of groundwater returned to the forefront [7]. The issue then was the rapid deterioration of wood piles within the one block; wood piles identified as sound in 1978 were found badly decayed just six years later due to a sudden and sustained change in groundwater level. The Boston Groundwater Trust (BGwT) was created in 1986 in part to measure and report on groundwater levels. The BGwT web-site {*www.Bostongroundwater.org*} contains significant amount of information on groundwater levels and the issues of wood piles.

The BGwT has installed approximately 725 observation wells since fall 2003 to re-establish the coverage that existed under the WPA program. The total network now numbers approximately 840 observations wells, with about 115 of these having been assimilated from earlier projects, including some from the original WPA project. The co-op students from Wentworth assisted with field monitoring of observation well installations and have been measuring water levels in the wells and reporting the data to the BGwT technical coordinator. Mr. Simonelli actually began work as a co-op student in his sophomore year a decade ago, searching for existing observations wells, testing wells, surveying rim elevations of roadway boxes and periodically making readings. There are now observation wells at every intersection and in the middle of long blocks throughout the filled land areas of Boston, with the same average coverage as shown in Figure 7.

The data on groundwater levels does show a number of areas of differing sizes where groundwater is below Elev. 5 (BCB). However, even the areas where groundwater is presently above Elev. 5 (BCB) may be in danger of having rotted wood pile tops because the top elevation of piles may be higher than Elev. 5. Now that the BGwT has re-established the groundwater level monitoring network, the remaining great unknown is the elevation of the tops of wood piles, and the composition of the fill soils that surround the piles and cap blocks. This first issue is expected to be the next area for student co-op research, with some trial field testing of certain geophysical methods expected later in 2008. If successful, it could avoid having to excavate 12 to 15 foot deep test pits to locate the tops of wood piles, which cost in the range of $4000 to $6000.

When wood pile tops do rot to the point that they can no longer support the weight of building loads, the wood at the top of the pile is crushed down a bit, and then a bit more as rotting continues. This causes building settlement to occur. Fortunately, there usually is not a sudden, dramatic collapse. As the pile cap settles with the crushing wood, the cap blocks become supported on the underlying uncompacted granular fill. However, the wood pile foundation is no longer providing the solid support to building loads that once existed and for which the building was designed, so pile repairs become necessary. The repair of rotted pile tops by the "tried and true" cut and post method is illustrated in Figure 8. Such repairs for a 'typical' rowhouse can easily cost $300,000 and often goes double that price, which is about 10% of rowhouse value in Back Bay. The co-op student in the Fall 2007 semester has been working on design of alternate methods for repair which are expected to be substantially cheaper than the cut and post method, as discussed below.

What Causes the Groundwater to be Lowered?

From an engineering or hydrogeology point of view, it is obvious that over the widespread area, the lowering of groundwater levels is being caused by the leaking of groundwater into man-made below ground structures, such as pipes, tunnels and basements. Why else would groundwater be lower than the Charles River, which is maintained between El. 7.5 and 8 (BCB)? Of course in the summer months when the weather is dry, the trees and evaporation can take substantial amounts of water out of the ground.

Of all the man-made structures in the ground, only the water pipes that bring fresh water to homes and businesses are under pressure and capable of being a *source* of water to the ground. All other pipes and conduits are largely empty, and therefore capable of allowing groundwater to enter. Tunnels, basements and all other underground spaces have the same potential when they are at levels lower than groundwater. The sewer pipes in much of Boston are combined sewerage and storm drains, and these are usually quite nearly empty, having been designed to handle storm run-off which is usually a far greater quantity than normal household wastewater. Furthermore, many were constructed more than 100 years ago when the common construction practice was to use an underdrain pipe below the sewer (see Figure 9) as a means of trench dewatering during pipe construction. These century old pipes were often constructed of two or three courses of brick masonry, which with time can experience some deterioration, and develop cracks and leaks. The original construction was slow, so an effective underdrain system was vital for keeping the trench drained. It is unlikely that any of the underdrains was ever backfilled after pipe building work passed by a location or manhole.

As time has passed, the infrastructure has aged, as have the buildings and tunnels. Additional leaks may occasionally open up. Because most of these leaks are undocumented, neither the magnitude of leakage nor the location of leaking is known. Finding the leaks will be difficult enough, but the repairs will be very challenging. The success of a repair will be in seeing the groundwater level rise in the observation wells in the immediate area around the repaired leaks. However, once one leak is plugged the groundwater will likely flow to the next higher leak. The continuing work of the co-op students in measuring water levels in the 840 observation wells every 6 to 8 weeks is therefore vital for the continuing surveillance of groundwater levels in the efforts for wood pile preservation.

Further complicating the problem is the fact that precipitation has very little access to enter the ground and reach the groundwater table. An observation from above a typical block of houses in Back Bay is shown in Figure 10 to illustrate just how little of the annual rainfall on the block can actually get into the ground. The area of the ground that is available for infiltration for this typical block is the small grass area at the front of the house, which is illustrated as the gray strip between the house and sidewalk to the front. The area is only about 5% of the block area. Most areas at the rear of the houses have been paved for parking. On that small "green" space, less than half of the rain that falls on the grass will actually seep into the ground. So for the typical block of houses in Back Bay that covers an area of about 2.5 acres, only 80,000 gallons of the annual 3,250,000 gallons of precipitation falling on the block can find its way into the ground (using the Boston average annual precipitation of 41 inches per year). That small amount of water over the area of the block of houses could only cause the groundwater table to rise 3 inches, assuming of course that none of the infiltration evaporated or was taken up by the tree root, or flowed away through the ground to other nearby areas or to leaky sewers.

The other 3,170,000 gallons of water is lost to the sewer system because so many roof drain downspouts are simply connected into the house plumbing or discharge onto paved surfaces. The rain falling on sidewalks and streets flows away to the street gutters and catch basins, as does the rain that falls on rear paved parking areas and alleys. The 3.17 million gallons of rainfall on that one block evolves to be a huge total volume when all the blocks of the filled land areas are considered, perhaps one billion gallons, or more. But precipitation occurs with great irregularity and sometimes at great intensity. So it is unlikely that putting the precipitation into the ground *by itself* can be the complete answer to the problem of preservation of wood piles, but it is a vital part of the solution. Student senior design capstone project in 2005 investigated means for recharge of precipitation, and environmental aspects of using surface runoff for a four block neighborhood in the South End. It was also determined necessary to include a perimeter cut-off barrier through the Fill stratum to retain the recharged water. The project was presented to a group of City and State representatives who have since authorized $2 million for actual installation of the cut-off barrier that would essentially create a groundwater "bath tub".

The possible drawdowns caused by groundwater withdrawals into leaking low lying structures is investigated for eight times a year using the water elevations determined by the students' measurements in the 840 observation wells. The data are first evaluated by Boston Water and Sewer Commission (BWSC) who develop a contour plan of groundwater levels. By studying the drawdown of groundwater levels and changes from previous dates, it is possible to focus on possible culprits. Sometimes the cause is not clear, and supplemental observation wells are installed to better define the localized groundwater regime. Finding the exact location of leakage so that repairs can be made requires further in-structure examinations is often practically impossible in old brick sewers, so full rehabilitation or relining is often undertaken. Much of the time, groundwater levels rise after repairs are made, but not necessarily by much more than a couple of inches. Finding one leak and fixing it often simply causes groundwater to run to the next higher leak.

All findable leakages into any below ground space should be plugged and stopped. What is known to leak at the present is without doubt only a minor sampling of the full list of all existing leaking infrastructure and buildings. For instance, there are known leakages into both the Storrow Drive Underpass along the Esplanade by the Charles River, and into the MBTA railroad structure just east of Back Bay Station. Leakages into the basement/former boiler room of the YWCA have recently been sealed; this leakage was previously of considerable quantity. Sewers and manholes have been found to leak along the alley behind Hemingway Street in the Fenway, on Dartmouth St near Beacon St, and along Back Street. Boston Water and Sewer Commission has been actively pursuing repairs to all suspected leaks. If job security were the primary goal for a new college graduate job-seeker, then repairing the leaking infrastructure of Boston could be a job high on the list. With a city underlain with miles upon miles of old pipes, the maintenance of the network and repair of leaks would appear to provide a never-ending list of work tasks.

Finally, there are those withdrawals of groundwater that are *planned* by the use of under slab drains. Actually, in most situations such drains are only active during and shortly after heavy rainfall when groundwater level rises. The inflow levels of these types of drains are set so that groundwater is only taken away when it rises to above a certain level; deep permanent underdrains that impact the fill stratum are no longer permitted. Unfortunately, underdrain systems in the past were not usually designed to take into account the needs of the wider spread surrounding area. In the past 15 years, several developers have installed underdrains below new parking garages under rowhouses that they were converting to condominiums. The parking is created by digging out 6 to 8 ft of fill from below the basement and installing a 6 to 8 inch thick concrete slab-on-grade. However, because a high groundwater level would cause uplift pressure on the bottom of the slab, a porous drainage layer is installed below the slab and pipes are provided to remove water that enters the system. Unfortunately, it has only been since 2005 that BGwT has had a role in review of such proposed developments and it is now required that such underdrains be planned with a first goal of keeping groundwater in the vicinity above the tops of wood piles.

Modeling of Groundwater is very Complex due to Subsurface Barriers

Simple contour modeling has been applied to help interpret data on groundwater levels that the BGwT collects and disseminates through their web-site. The BWSC uses the data to produce groundwater level contours which visually 'point out' depressions in the groundwater table. These are drawn using simple contouring program that applies free-field without regard to the thickness of the fill stratum, its interconnection to the outwash stratum, or basements of buildings, tunnels or other barriers to subsurface flow. Although not a fully accurate representation, the BWSC contours do serve a very useful purpose of directing attention to pipes and drains in the vicinity of the depressions. When isolated mounds appear, these often indicate water main leaks and trigger similar investigations. In the future, more accurate modeling will likely be undertaken as research effort, primarily to assess the usefulness and affect of certain recharge efforts or the installation of new barriers in the fill stratum.

There are numerous barriers to groundwater throughout the filled land area. The creation of the Back Bay for harnessing tidal power for mills in 1820 created the largest barrier, the Mill Dam, upon which Beacon Street was built. This dam lies just one block inland from the Charles River. The mud-fill core of the 50 ft. wide dam is quite effective in preventing water from the Charles River from seeping through the fill to replenish groundwater in Back Bay. Tunnels are also sometimes barriers to groundwater, such as the subway tunnel constructed in 1912-14 beneath Boylston Street, four blocks east of Beacon Street. But in the case of the more recently constructed Orange Line subway and railroad tunnel through Back Bay, special provisions of numerous pipes and drains were incorporated into the 1980's construction to permit cross-alignment flow of groundwater.

Buildings and development areas may also become barriers to groundwater flow. For instance, the seven block area of the Prudential Center is for the most part ringed with a steel sheet pile cofferdam to cut it off from the local surrounding groundwater regime. This is an excellent example of positive isolation to prevent there from being effect outside the area of the below grade parking garage. There are several other examples of full or half block deep basements which penetrate down through the Fill stratum and the Organic Silt and into the deeper clay.

It is now being considered that additional barriers may be necessary in some instances to interrupt groundwater flow toward withdrawals that can not be reasonably accessed or where it will not be possible to specifically identify the exact cause of groundwater lowering. In such instances, it might be more practical to install subsurface flow barriers to block the drawdown, or to totally contain an area to make the groundwater stay around the area of concern. Of course such installations should not be undertaken without full study and modeling of the local and wider regional groundwater regime and predictions of the groundwater flow and levels that will result after the barrier is installed and develop mitigation scenarios if behavior is not as expected.

In one rather isolated area, a boat section railroad and subway structure that lies just east of the Back Bay Station railroad platforms is considered to be a cause of groundwater lowering in the St. Charles and Cazenove Street area of the South End neighborhood. The exact location of leak(s) has not been established, and direct repairs are considered impractical from a railroad operations point of view. As mentioned earlier, one possible solution was studied by students at Wentworth Institute of Technology for their Capstone Senior Design project in 2005. Part of their solution was an impervious barrier that penetrates down through the Fill into the underlying Organic Silt. A detailed study of the potential impact of barrier wall installation on the regional groundwater flow regime was beyond the scope of the students' design project; it awaits a senior seeking a special topic study.

Recharging to Raise and Preserve Groundwater Levels

The application of recharge systems to permit direct infiltration of precipitation into the ground has been done for decades in Boston, but only in a few isolated areas. A major recharge system exists at the Copley Square plaza in front of Trinity Church, which is just across Dartmouth Street from the Boston Public Library where rotted piles required repair in 1929. The Copley Square recharge uses a system of 12 to 20 inch diameter perforated pipes set in beds of gravel to permit the surface drainage from the sidewalks and grass areas of the Square to be infiltrated directly into the ground. The current system is the third generation installed at Copley Square. Virtually no precipitation water runs off to the street gutters or drains. Also, Trinity Church has for decades taken their roof drainage and directed it into their observation/recharge pits (which were originally dug in the 1930s to permit inspection of some of the 4,500 wood piles that support this massive and historic structure.

Recharge systems that use sidewalk or rooftop precipitation run the risk of becoming clogged with time as fine particulate matter and soil particles are carried into the system. Some periodic maintenance is therefore needed to continue the efficient operation of the recharge gallery. Such maintenance would at a minimum have to clean the inlet basin (where water should first be directed to permit settling out of "grit". The annual removal of grit and organic matter will greatly prolong the effective life of a given recharge installation, and the lack of maintenance will shorten the system's life (to as little as 5 to 10 years).

In other instances, recharge systems exist that are only operated when groundwater levels recede below 'threshold' levels. Such systems are at the Boston Public Library and Lenox Hotel (both of which use tap water), and in the lower Beacon Hill area at the Church of the Advent (which uses water pumped from the deep glacial till and bedrock aquifers). As a trial, three recharge wells have been installed in the St. Charles Street neighborhood to determine how much water is required to raise and maintain groundwater levels above El. 5 (BCB). The St. Charles Street recharge system is also determining the radius of influence of the recharge source so estimates can be drawn as to what the area-wide need for numbers of recharge wells might be.

Examples of recharging in the Back Bay have been very few, but are vitally needed due to the predominance of impervious surfaces. A remedy was instituted in 2005 when the Boston Redevelopment Authority enacted Groundwater Overlay District designation for certain areas. This now requires recharge systems be installed for both new development projects and buildings undergoing substantial renovation to channel most of the rooftop precipitation into the ground. Thus, over a number of years, the usual practice of sending thousands of gallons of water to the sewers with every rain event will end as drywell recharge systems such as shown schematically in Figure 11. These systems will need overflow or detention tanks to accommodate periods of very intense and sustained rainfall. Such systems will not be below every yard overnight, or even in 5 years, but with the concerted effort through public policy, then in two or three decades, the groundwater recharge would be expected to positive effect on raising groundwater levels. Just remember, curb-ramps for handicapped access at intersections took several decades to appear at every cross-walk.

To design recharge systems, information is necessary on the permeability of the Fill stratum and the depth of Fill above the underlying impervious stratum. An initial research effort was undertaken in 2006 by two civil engineering seniors Wentworth as a special topics study course in which they characterized the granular fill in two neighborhoods[13]. Soil samples retrieved from Standard Penetration Tests made during observation well installations were tested by sieve and hydrometer analysis to determine the gradation of the fill. Results of some tests are shown on Figure 12 as grain size distribution of several samples from the South End, and then as a summary graph comparing distribution of various samples for the granular soil characterization. The fill has been found to be of fairly consistent gradation throughout most of the Back Bay neighborhood, but shows great variability in the South End with several samples having substantial amount of fines (minus No. 200 sieve). Further testing to characterize the fill in other neighborhoods is expected to be taken up by two seniors this coming year who will also attempt permeability tests on composite samples of same gradation. The intent is to develop reasonable ranges for fill permeability in the various neighborhoods, and provide guidance on correlations of grain size and permeability. This is an important parameter for geotechnical engineers and hydrologists who will design future recharge systems.

The work of the students in 2006 also resulted in contour maps of the elevation of the bottom of the fill stratum, using data from the test borings made for observation well installations. Further work is needed to incorporate other data from independent sources, such as logs of borings historically compiled by the Boston Society of Civil Engineers[14], and more recent test boring work done for proposed real estate development and infrastructure projects. The thickness of the Fill stratum available to receive the recharge is fairly well defined by the contours of the bottom of the Fill stratum that are also being developed as part of the research. In the future, when it is desired to undertake the design of a recharge system, it is anticipated that preliminary designs could be accomplished with only the subsurface information and design parameters that will be developed from the Wentworth research.

Alternative Replacement Foundation Systems instead of Traditional Underpinning

A study is currently underway by the author and a co-op student to investigate an alternative method to the traditional cut and post underpinning, which was noted above as being shown on

Figure 8. The alternative involves forming a concrete *'mat-slab'* within the footprint of the house to carry the weight of the house to the fill soil between the walls, as illustrated in Figure 13. The slab will be 'framed' into the perimeter brick party and foundation walls of the house at the slab bearing level. The load of the house will then be transferred to the fill stratum rather than at the deeper level of the ends of the wood piles some 15 ft to 35 ft below the house on the hard crust of the clay or sand stratum. The intent of the study is to assess less expensive methods of underpinning, which would have particular application in some of the less expensive neighborhoods, such as in East Boston where house values are an order of magnitude lower than in Back Bay. During the fall 2007 semester, a co-op civil engineering student worked for the Boston Groundwater Trust both reading observation well levels and performing design analyses and preparing construction drawings for the 'mat-slab' system.

A number of design aspects have been evaluated by the co-op student. First assessment was to determine the loads for the rowhouses based on Massachusetts Building Code. With the loading for each wall, analyses were then made for reinforced concrete structural slab thickness and necessary reinforcing steel, for which several different distributions of soil contact pressure were used. The structural design for a 'typical' house would require an 18 inch thick slab with No. 8 reinforcing bars set at 10 inch spacings in the top and No. 4 bars in the bottom, in both transverse and longitudinal directions across the full 20 ft by 45 ft footprint. Then, the student made calculations of the potential settlement that could occur due to the mat-slab loading on the granular fill and underlying organic soils (both immediate and consolidation), the total of which was estimated to be approximately 0.3 inches. Finally, soil-structure interaction analysis using the program PLAXIS was attempted to determine which of the soil reaction distributions used in the reinforced concrete design was the most appropriate.

During the project, the City of Boston proposed a trial be made on a single house which the city owns due to delinquent tax issues. The student prepared construction drawings at the author's direction and a specification for the work was drafted, and proposal obtained from a contractor with the intention that the construction would be performed in 2008. Several aspects of the construction will be closely observed, in particular the inserting of concrete connections into the brick perimeter walls, prior to main slab construction. It is hoped that the overall cost for installing such a mat-slab can be reduced to less than $100,000 per house.

Other structural re-support systems that are being considered in lieu of the cut and post method underpinning are shown on Figure 14. It has been suggested that it might be feasible to inject cement-based grout into the granular fill below the granite block pile caps to solidify the granular fill in the several feet below the granite block pile caps. However the ability to drill the distances necessary and the locating of the proper position for this grouting have not be reliably addressed. Also shown on Figure 14 is an alternative support system using "bracket piles". In such repairs, new piles (small diameter steel pipes or screwed-in full flight augers) are pushed or drilled into the ground next to the party wall and front and rear walls, and a structural steel frame bracket system is used to attach the pile top to the brick party wall. A concern with this system is that the bracket system may be introducing a different stress regime into the brick bearing walls due to attachment support on only one side of the wall. Further analysis has to be made on structural load change that the bracket would impose on the brick party walls because these walls are already 100 to 150 years old, and must not be overstressed in bending moment loading.

Summary

The relationship between groundwater and wood piles is quite tenuous. Lowering of groundwater can cost the homeowner several hundred thousand dollars to repair wood piles. However, with proper forethought and directed action, the problems of the past can be averted. But it takes constant vigilance to monitor the groundwater table levels and take immediate action when lowering is first observed. Fortunately, there is some time between the first occurrence of groundwater lowering and the compromise of load support available from wood piles. But concerted efforts are needed. This is all the more vital in Boston where the infrastructure is old. There is also vital need for replenishing the groundwater table by using rainfall recharging systems. Current regulations will force their use at every renovated rowhouse and new development to redirect roof run-off into recharge systems.

Work by co-op students from Wentworth and seniors who undertake special topic studies has greatly added to knowledge on groundwater levels and fill stratum characterization. Design options have looked into recharging and now alternative rowhouse support methods. The students gain an appreciation for these local problems and better understand the far reach of issues that must be addressed in such an encompassing area-wide project.

Bibliographic Information

1. Seasholes, N., Gaining Ground, MIT Press, 2003.
2. Skehan, J., The Roadside Geology of Massachusetts, Mountain Publishing Co., 2001.
3. Barosh, P., Kaye, C., and Woodhouse, D., "Geology of the Boston Basin & Vicinity," Civil Engineering Practice – Journal of the Boston Society of Civil Engineers Section, ASCE, Vol. 4, No. 1, Spring, 1989.
4. Newman, W. and Holton, W., Boston's Back Bay, Northeastern University Press, Boston, MA, 2006.
5. Kaye, C., "Bedrock and Quaternary Geology of the Boston Area, Massachusetts," Geological Society of America, Reviews in Engineering Geology, Vol. V, 1982, pp. 25-40.
6. Bunting, B., Houses of Boston's Back Bay, The Belknap Press of Harvard University, 1967.
7. Lambrechts, J., "Investigating the Cause of Rotted Wood Piles," Second Forensic Engineering Congress, American Society of Civil Engineers, San Juan, PR., 2000.
8. Aldrich, H.P. and Lambrechts, J.R., "Back Bay Boston – Part II, Groundwater Levels," Civil Engineering Practice – Journal of the Boston Society of Civil Engineers Section, ASCE, Vol. 1, No. 2, Fall, 1986.
9. Cotton, J.E. and Delaney, D.F., "Groundwater Levels on Boston Peninsula, Massachusetts," Hydrologic Investigation Atlas HA-513, U.S.Geological Survey, Reston, VA, 1975, 4 sheets.
10. Stearns, F.P. , "Report of the Joint Board Upon the Improvement of Charles River, House No. 775, April 1894.
11. Worcester, J.R., "Boston Foundations," Journal of the Boston Society of Civil Engineers, Vol. 1, No. 1, 1914, with discussions pp. 179-248 and 395-417.
12. Paine, R.T., Trinity Church – The Church Endangered by Low Level of Ground Water – How the Danger Has Been Temporarily Averted, report dated April 20, 1935
13. Lambrechts, J., Keepers, A. and McCarthy, K., "What is the Fill? And What Does it Matter?," Paper prepared for the Massachusetts Historical Society Environmental History Seminar Series, Boston, MA, April, 2006.
14. Boston Society of Civil Engineers, "Boring Logs of the Boston Peninsula," Journal of the Boston Society of Civil Engineers, Vol. 57, No. 2, July, 1970.

Table I. Summary of Student Co-op Work for the Boston Groundwater Trust, and Other Special Studies Related to Groundwater Preservation and Wood Pile Repair Alternatives

Activity	Years	Students Involved	Findings / Results
Observation Well Locating and Network Development (co-op)	1999-2002	Kurt Victor, Christian Simonelli and Matthew White	Located approx. 125 existing OW's that had been installed for earlier construction projects. Surveyed to determine rim elevations using existing benchmarks.
Observation Well Water Level Measurements (co-op)	1999-2008 continuing	Christian Simonelli, Matthew White, Glauber DeJusus, Jake Leahey, Ryan McTigue, Ashley Keepers, Steve Guarente, Jessica Gormley, Cao LeDang	Measuring the depth to water in each OW on a 6 to 8 week frequency (depending on winter weather). Data entered into spreadsheet and data base for public access.
Monitoring Installation of more than 700 Observations Wells (co-op)	2003-2006	Christian Simonelli*, Jake Leahey, Ashley Keepers, Derek Barnes, Steve Guarente, Jessica Gormley	Monitored drilling operations through city sidewalks and documented conditions, N-values and verified proper installations (depths generally 17 to 25 ft.)
Building Dept. Records Research (co-op)	2004-2006	Ryan McTigue, Steve Guarente	Research through 143 volumes of Building Inspector Reports (1887-1923) and building permit records in search of information on wood pile top (cut-off) elevations.
Recharge to Raise Groundwater Levels in the South End Area (Senior Design Capstone Project)	Summer 2005	Jake Leahey, Ryan McTigue, Dan Walton	Developed recharge system to use roof run-off over a 4 block area in conjunction with perimeter cut-off wall using jet grout to raise and maintain groundwater.
Fill Stratum Thickness, Density and Soil Sample Gradations (Research Special Project)	Spring and Summer 2006	Ashley Keepers, Katelyn McCarthy, Steve Guarente	Performed lab. sieve and hydrometer testing for grain size on 100+ samples, and developed contour of Fill bottom Elev.
Alternate Mat-Slab Foundation instead of Traditional Underpinning (co-op)	Summer and Fall 2007	Cao LeDang	Structural analysis for reinforced concrete Mat-Slab, and development of construction drawings for trial installation.

* Christian Simonelli became a full-time employee of the Boston Groundwater Trust in 2003, after completing 3-1/2 years of co-op and part-time work with BGwT, and continues today as Technical Coordinator.

Figure 1. Examples of Wood Piles That Have Suffered Substantial Rotting

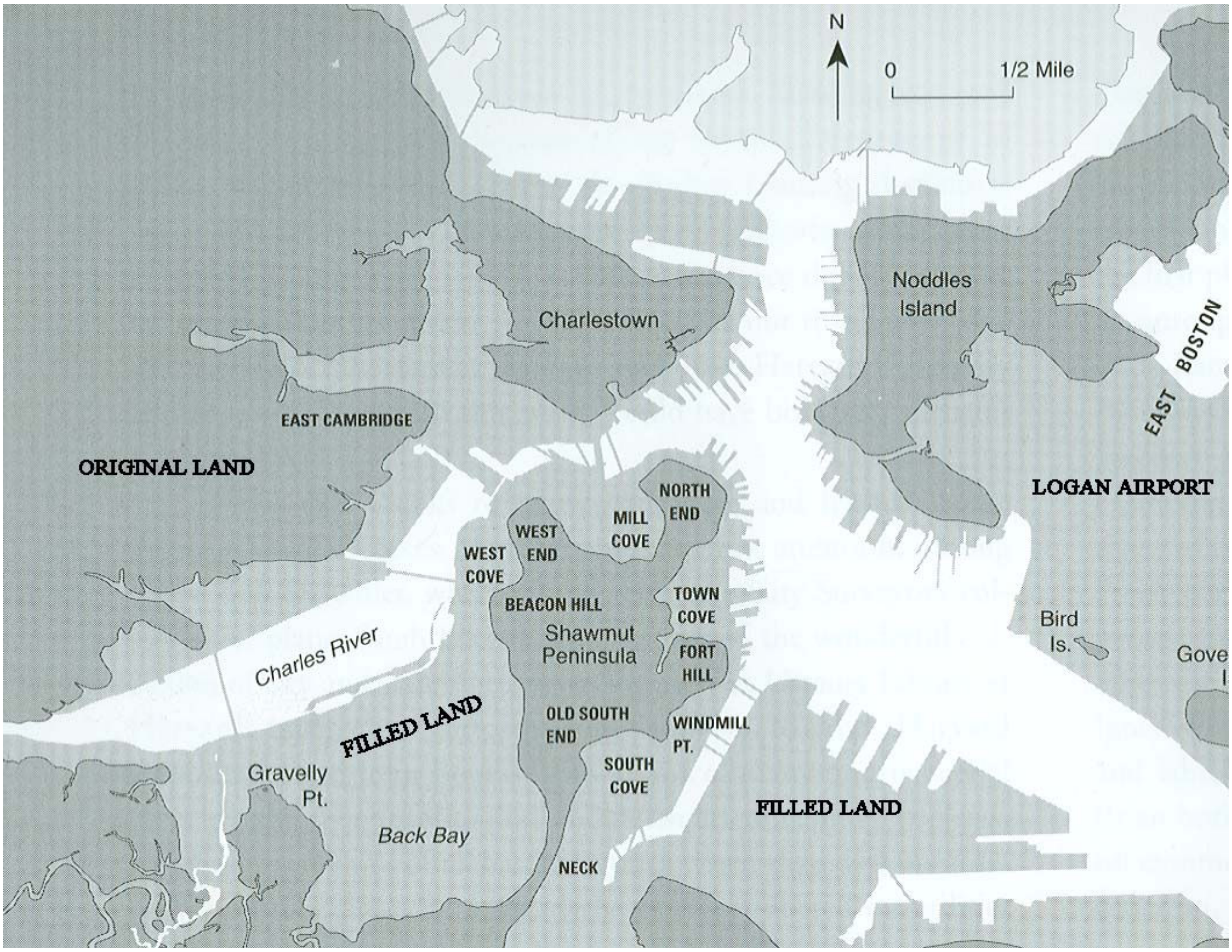


Figure 2. Original Colonial Shoreline of Boston Peninsula and Surrounding Areas, and Extent of Filled Land, from Seasholes, 2003

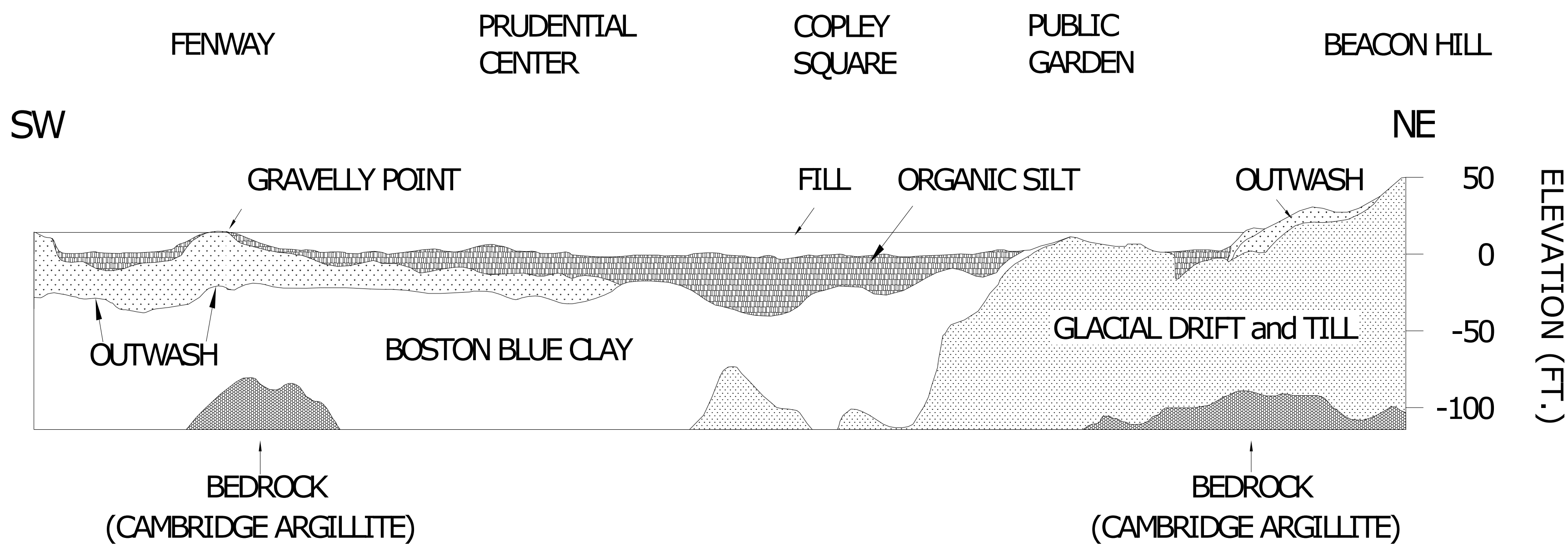


Figure 3. Subsurface Section Showing Soil Strata across Back Bay, Beacon Hill to Fenway (after Kaye, 1982)

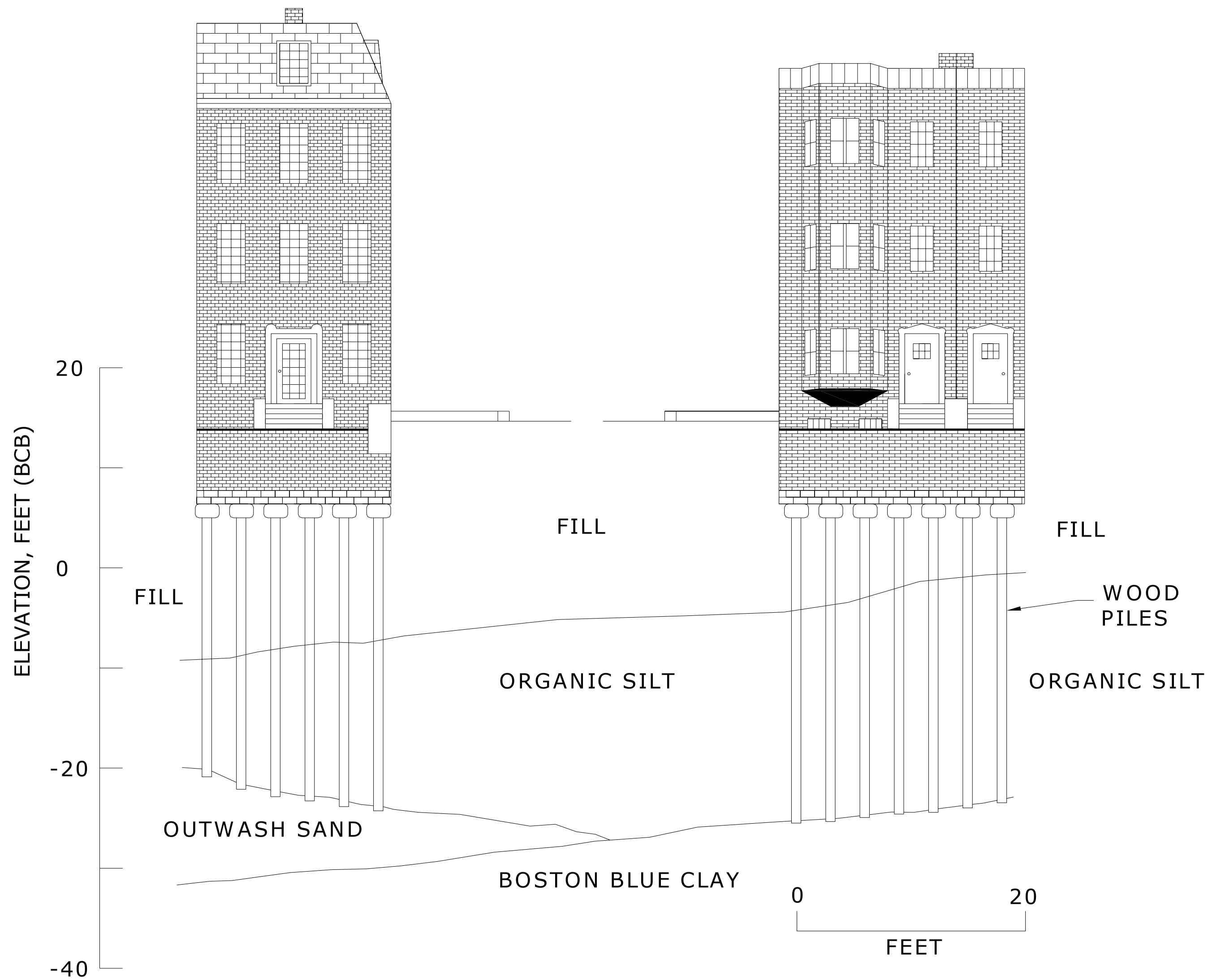


Figure 4. Use of Wood Piles to Support Rowhouses

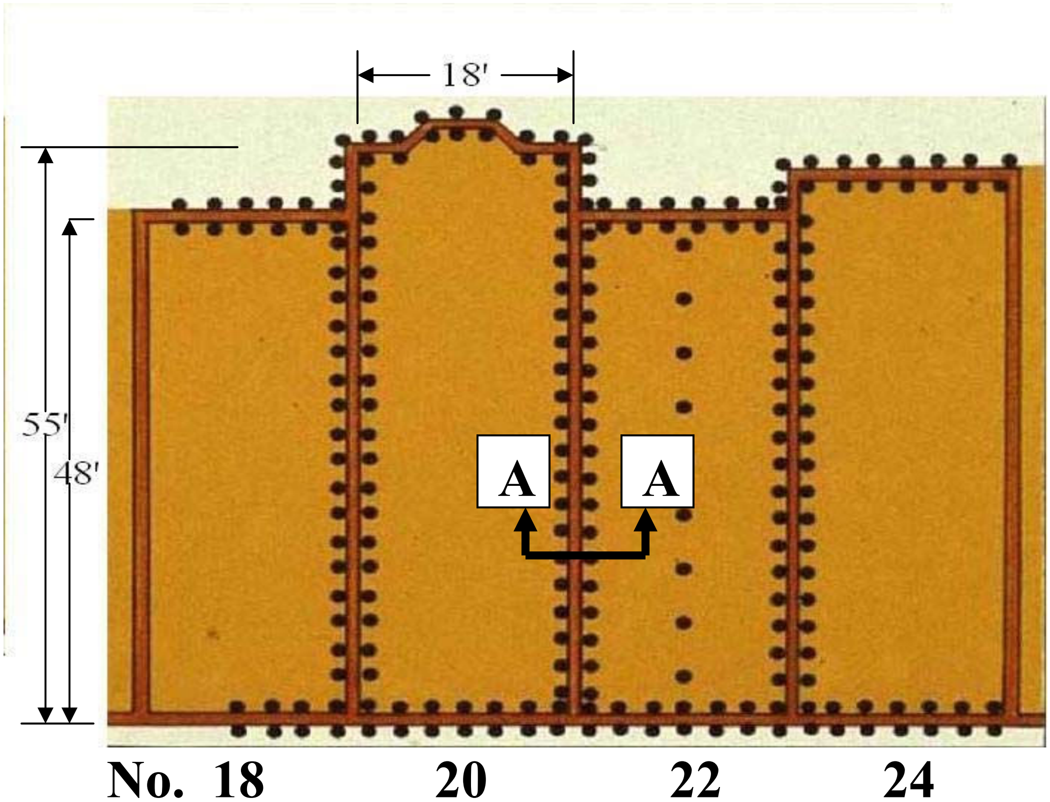


Figure 5. Plan of Typical Arrangement of Wood Piles beneath Rowhouse Wall

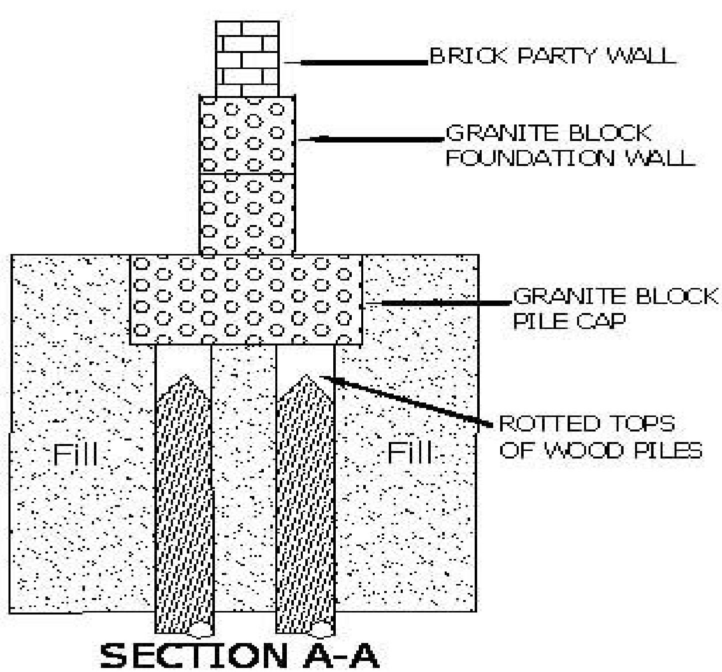


Figure 6. Cross Section of Granite Block Pile Cap Supported on Wood Pile and Foundation Walls Above

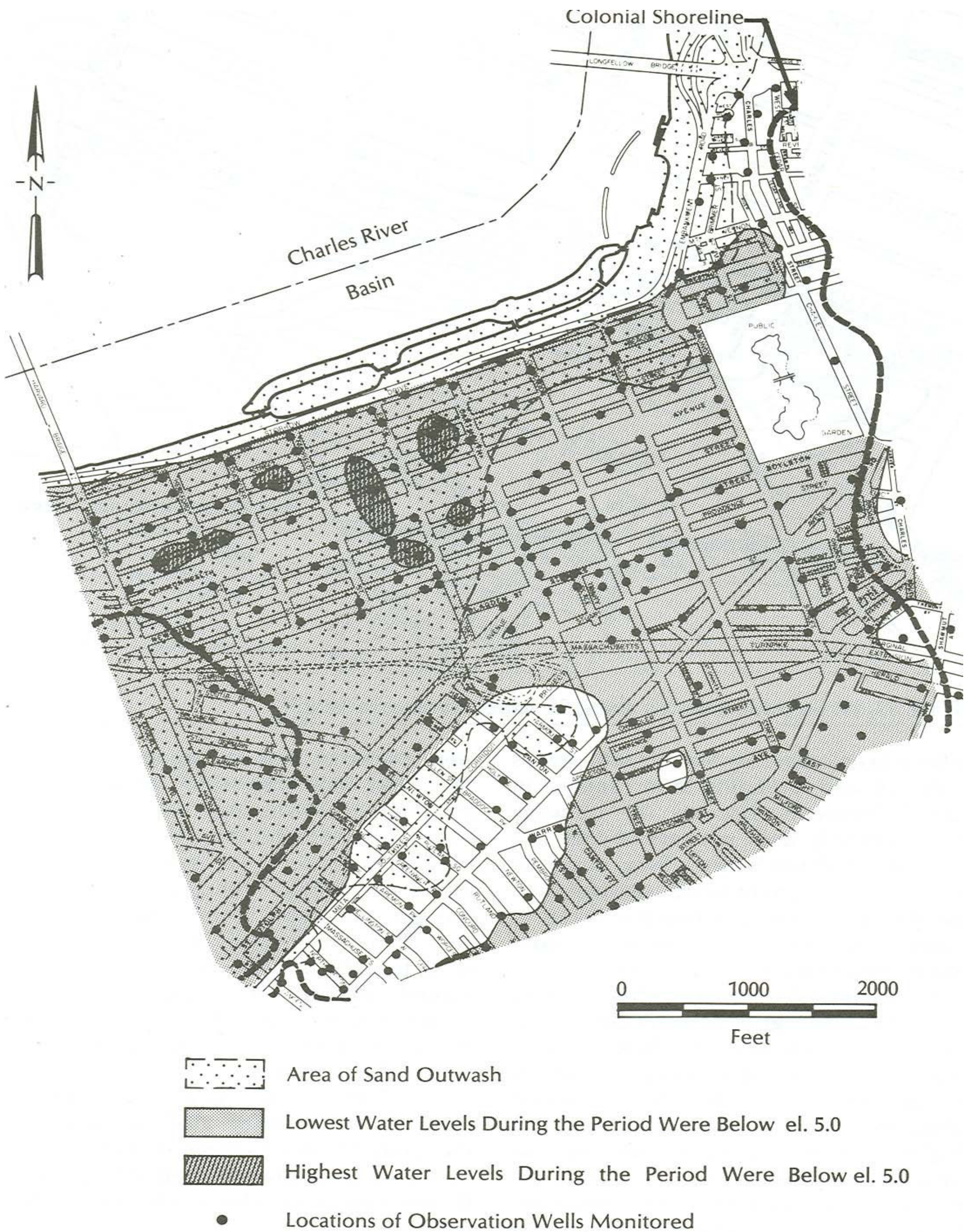


Figure 7. Area of Back Bay with Outwash Sand, and 1936-1940 Groundwater Levels, from Aldrich and Lambrechts, 1986

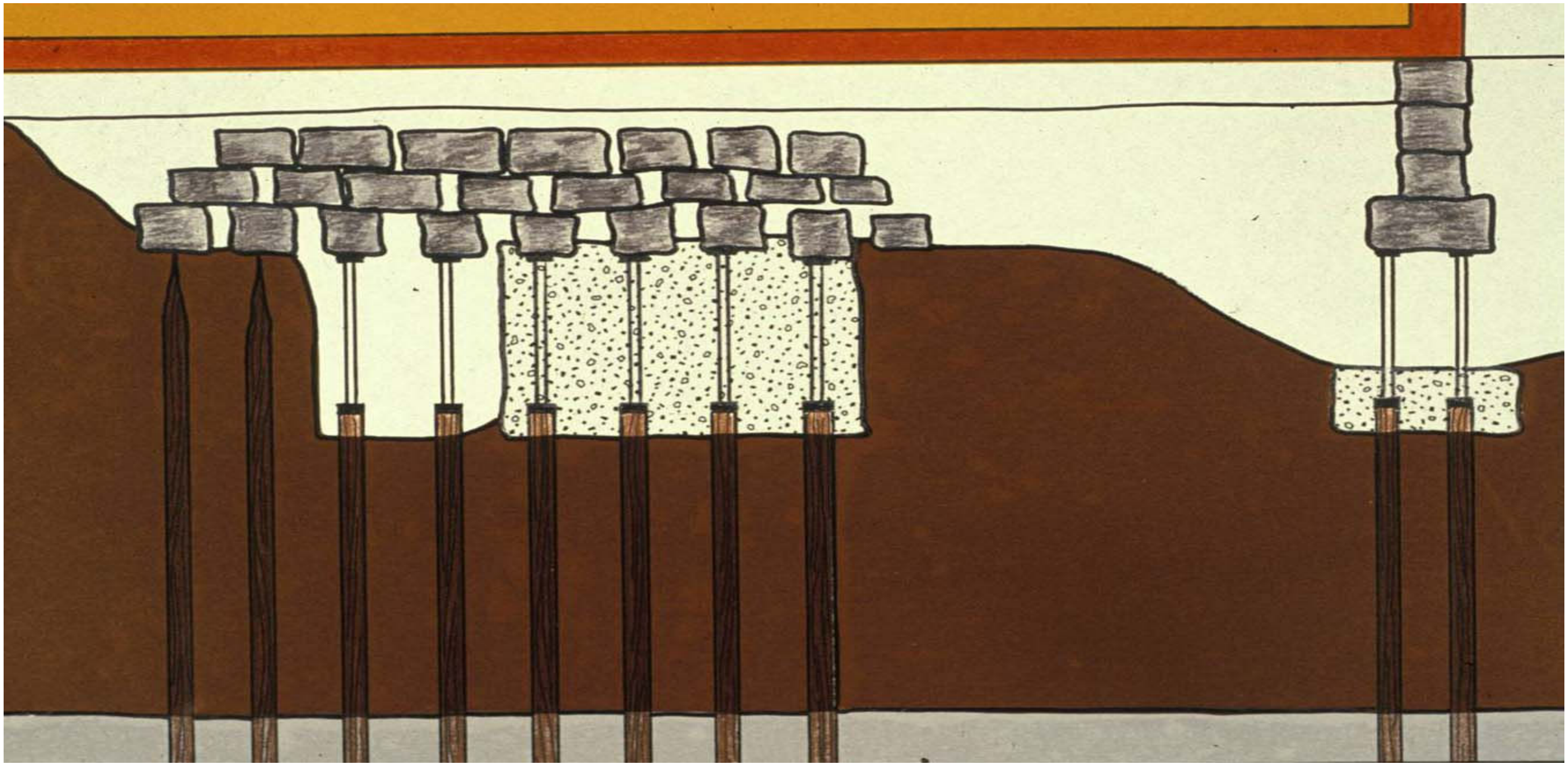


Figure 8. Illustration of Underpinning Sequence Used to Replace and Lower Wood Pile Tops that have Rotted

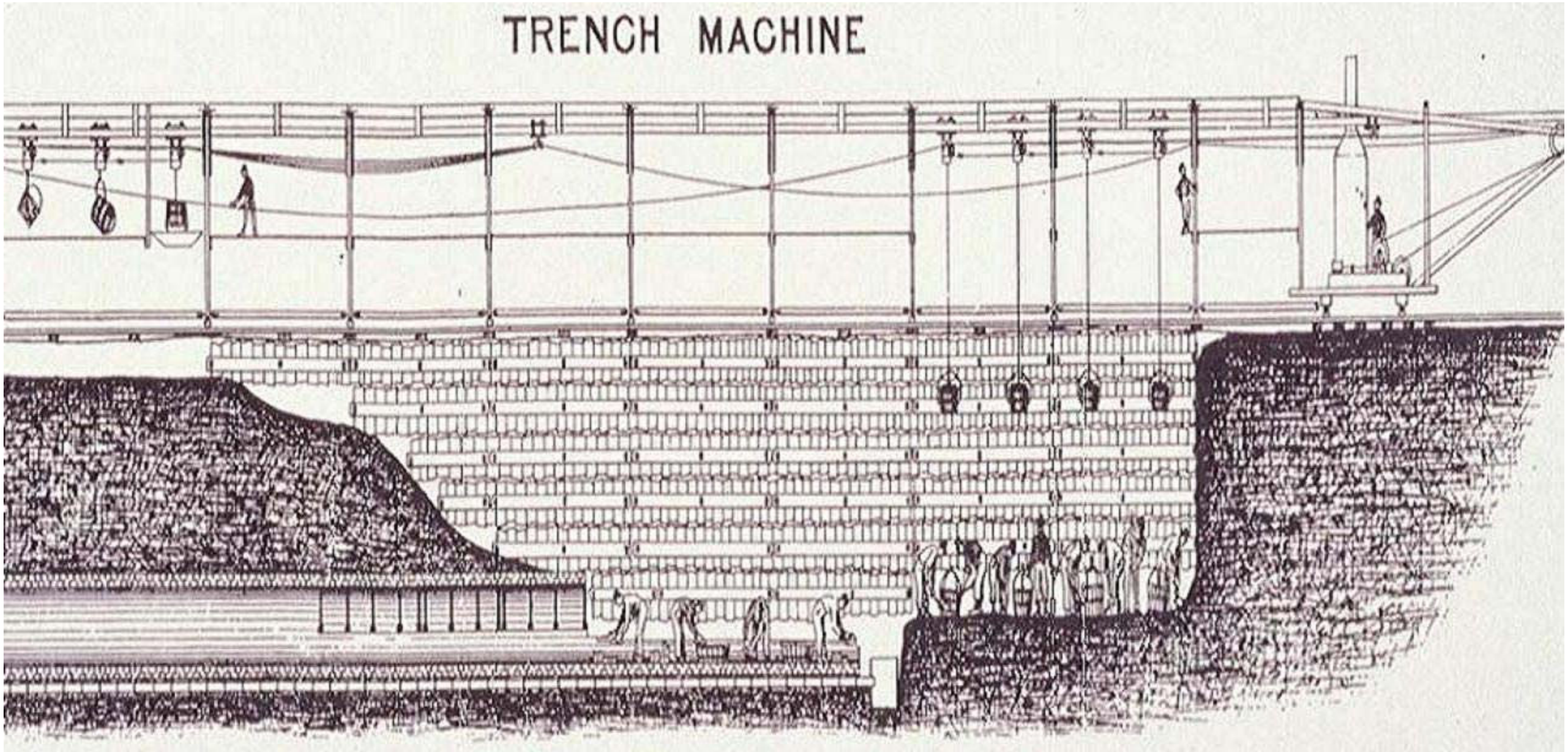


Figure 9. Trench Machine, Circa 1875, Used to Construct Deep Sewers in Filled Land Areas

Figure 10. Plan of Typical Block of Back Bay showing Limited Area Available for Precipitation Infiltration

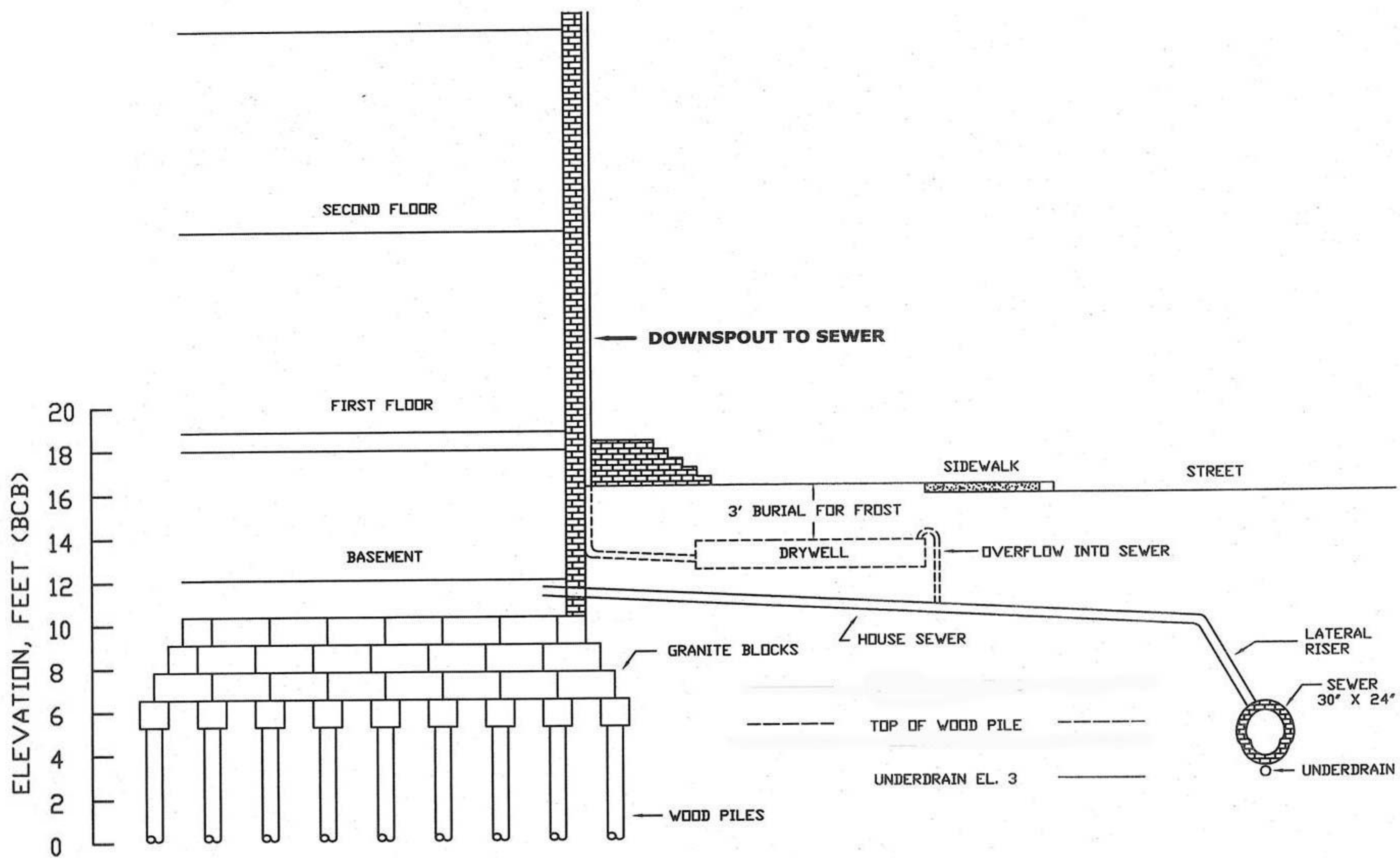


Figure 11. Cross Section View of Rowhouse Sewer Connection Showing Potential Recharge Drywell

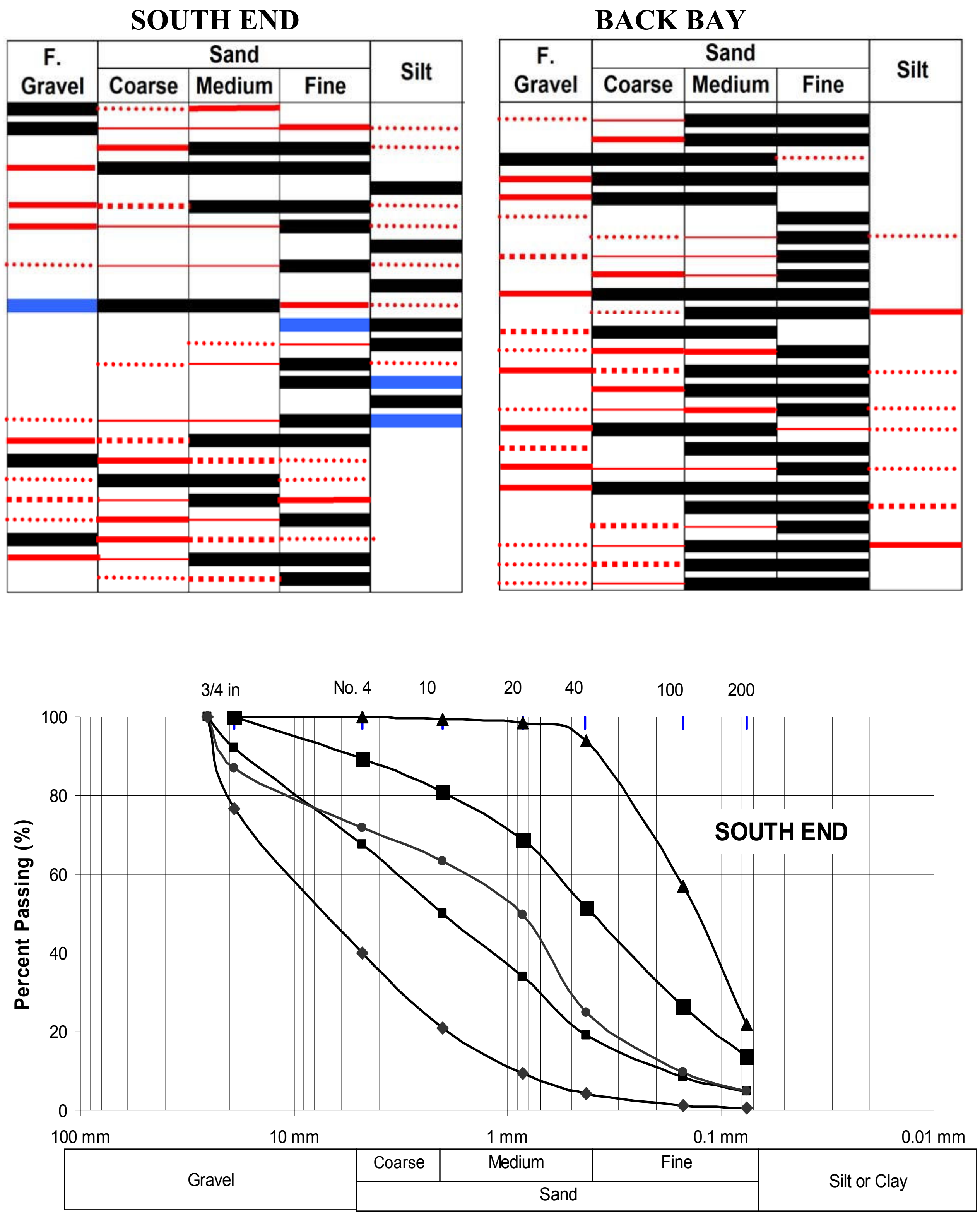


Figure 12. Grain Size Analysis on Samples of Fill Stratum

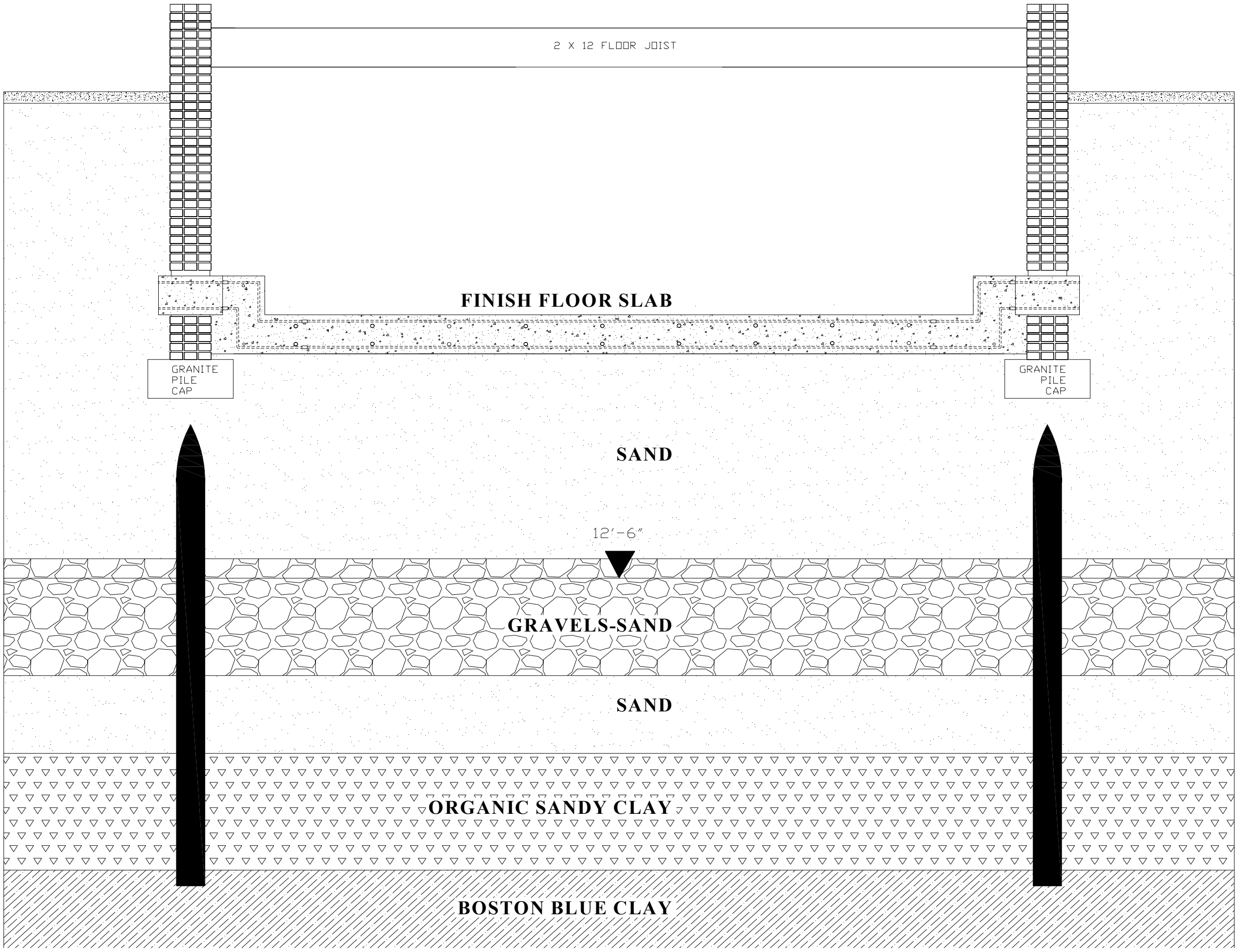
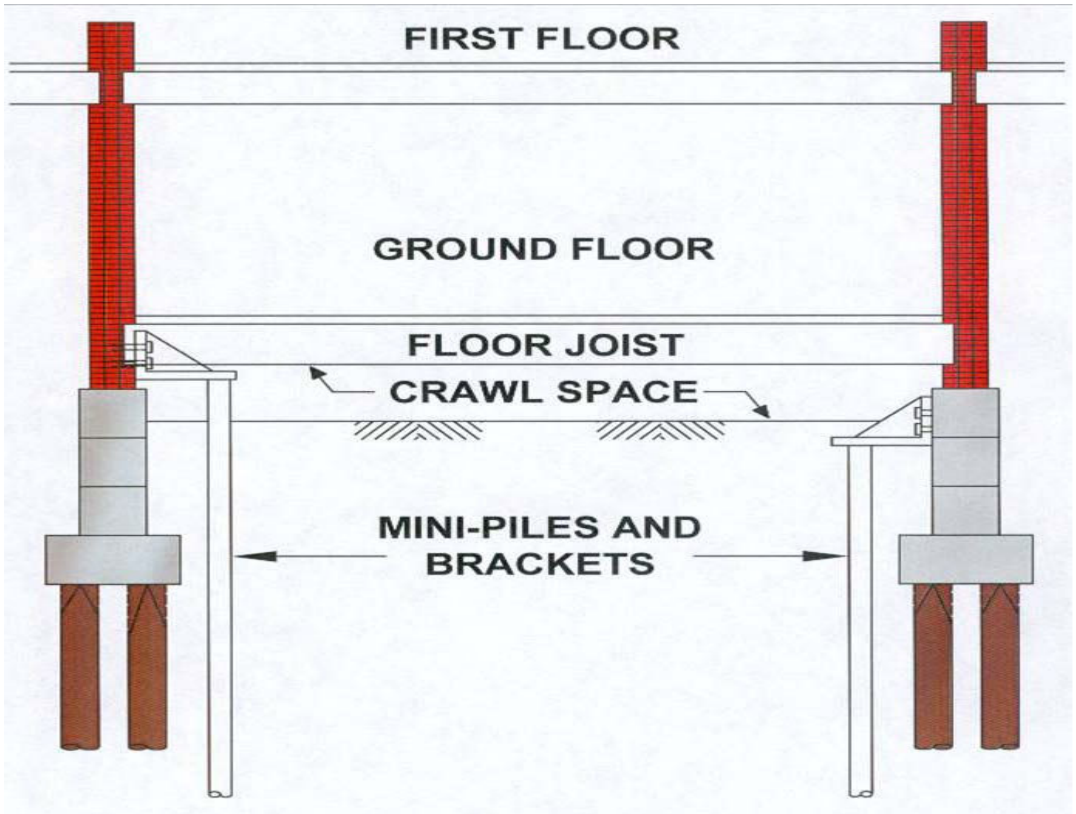


Figure 13. Reinforced Concrete Mat-Slab as Replacement for Wood Pile Foundations



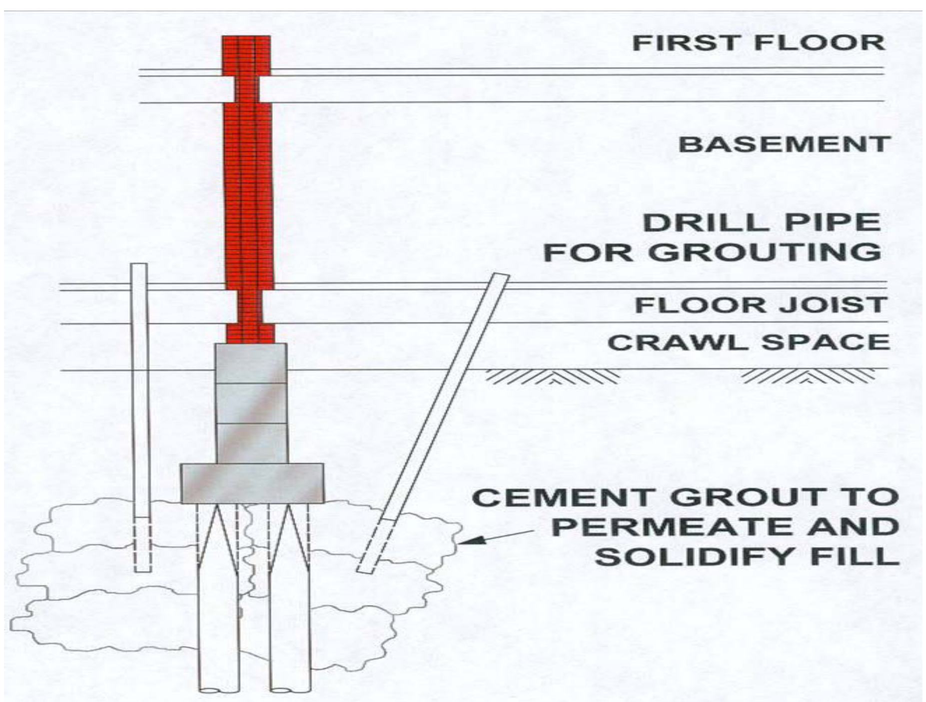


Figure 14. Possible Alternatives to Wood Piles Repair; Installing New Piles or Grouting