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Liquefaction Susceptibility Mapping in Boston, Massachusetts

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ABSTRACT

The Boston, Massachusetts, metropolitan area has experienced several historic earthquakes of about magnitude 6.0. A compilation of surficial geologic maps of the Boston, Massachusetts, metropolitan area and geotechnical analyses of Quaternary sedimentary deposits using nearly 3,000 geotechnical borehole logs reveal varying levels of susceptibility of these units to earthquake-induced liquefaction, given the generally accepted design earthquake for the region (M6.0 with 0.12*g* Peak Ground Acceleration (PGA)). The majority of the boreholes are located within the extensive downtown artificial fill units, but they also allow characterization of the natural deposits outside the downtown area. The geotechnical data were complemented with surficial geologic mapping, combining published and unpublished geologic maps, aerial photographic interpretation, and soil stratigraphy data from an additional 12,000 geotechnical boring logs. Susceptibility maps were developed based on liquefaction-triggering threshold ground motions, which were determined using the borehole data. We find that much of the non-engineered artificial fill that underlies the downtown Boston area is, when saturated, highly susceptible to liquefaction during seismic loading. Holocene alluvial and marsh deposits in the region are also moderately to highly susceptible to liquefaction. Much of the outlying area is underlain by Pleistocene and Quaternary glacial and glaciofluvial deposits, which have low to moderate susceptibility to liquefaction. This study provides data needed to effectively manage liquefaction hazards in the Boston area, and it will assist in characterizing seismic hazards, mitigating risks, and providing information for urban planning and emergency response.

INTRODUCTION

Boston, Massachusetts, is located in a region of moderate historic seismicity, where several historical events of about M6.0 have occurred (e.g., 1727, 1755). The possibility therefore exists for the generation of earthquake-induced liquefaction of near-surface sediments in the Boston area. In this paper, we present results of a study to assess the liquefaction susceptibility of natural sediments and areas of artificial fill in the Boston metropolitan area, with the aim of characterizing liquefaction hazard and providing information to local communities for improved planning and mitigation strategies. The primary goal of the study was to develop liquefaction susceptibility maps by combining surficial geologic mapping with subsurface borehole data. To develop these maps, existing surficial geologic maps at various scales were augmented with field reconnaissance mapping to provide a base for assessing the properties of the geologic units. An extensive digital borehole database was compiled to provide data on the subsurface properties; it is composed of nearly 3,000 borings, and it focuses on the artificial fill units in downtown Boston but also provides coverage of the other geologic units. The subsurface properties, including soil type, standard penetration test blow counts, and estimated fines content, were used to determine liquefaction susceptibility of each individual sample in the database. The liquefaction susceptibility mapping used the results of both the surficial geologic mapping and the subsurface sample liquefaction susceptibility analysis.

The study area encompasses eight 1:24,000-scale (7.5 minute) quadrangles in the metropolitan Boston region, and it includes the downtown Boston area and

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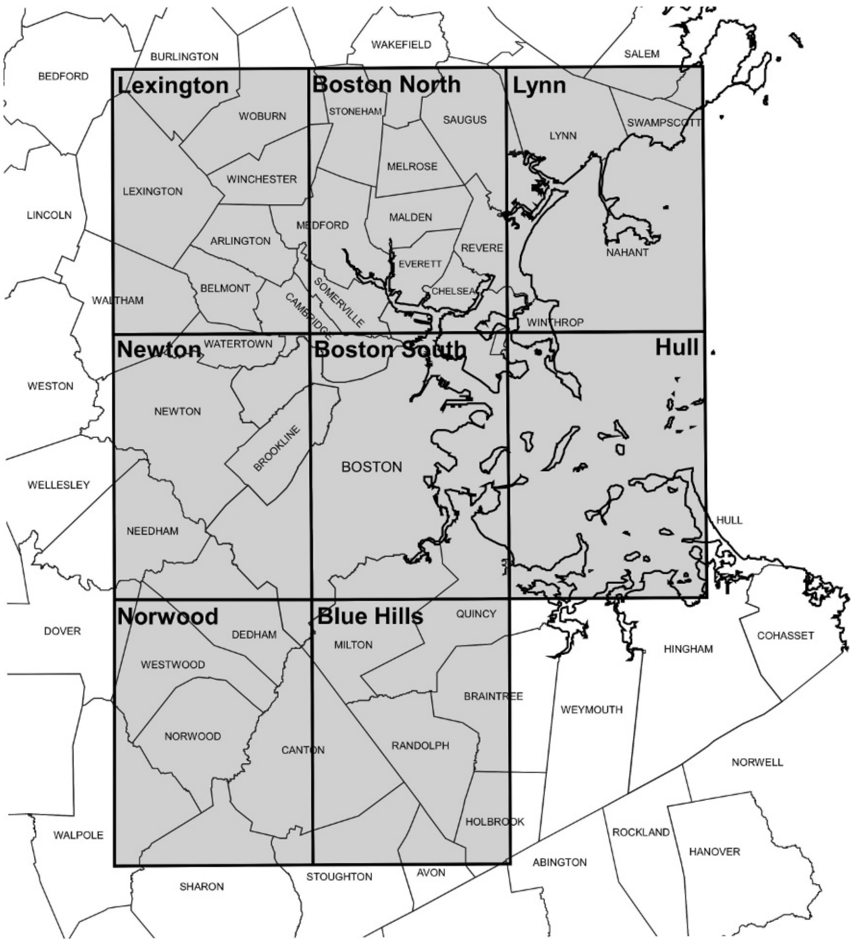

Figure 1. Quadrangle outline map of the greater Boston region showing community boundaries.

surrounding communities (Figure 1). Much of the region is underlain by Pleistocene and Quaternary glacial till and glaciofluvial deposits, as well as large areas of marsh deposits and extensive regions of non-engineered artificial fill. Based on their composition and conditions of geologic deposition, glaciofluvial deposits, marsh deposits, and especially the non-engineered artificial fill are potentially susceptible to liquefaction during large earthquakes.

BACKGROUND

Seismic History

The Boston region has experienced several historic earthquakes that have caused ground motions significant enough to trigger liquefaction in susceptible sediments. In 1638, an earthquake thought to have been located in central New Hampshire struck with a magnitude (M_{bLg}) of about 6.5; Ebel (1996, 1999) estimated that the event produced modified Mercalli intensity (MMI) of V–VII in Boston. An earthquake in 1663 located within the Charlevoix seismic zone in southern Quebec had a magnitude of about 7.0 and caused ground shaking intensity in Boston of at least V–VI, resulting in damage to several chimneys in the Boston area (Crosby, 1923; Ebel, 1996). The 1727 Newbury earthquake occurred approximately 56 km northeast of Boston, with an estimated moment magnitude (M_w) of 5.6, a reported local MMI of VI–VII, and a MMI for Boston and northern suburbs of V–VI (Ebel, 2000). Reports in Newbury at the time of the earthquake describe sand boils, which indicate liquefaction (Plant, 1742; Ebel, 2000). These occurrences of liquefaction have been confirmed by paleoseismic studies, which found sand dikes and sills in glaciomarine sediments in two locations corresponding to the liquefaction during the 1727 earthquake and one prehistoric event (Tuttle and Seeber, 1991; Tuttle et al., 2000).

The 1755 Cape Ann earthquake was the largest earthquake to have affected Boston in historic times, and it caused damage throughout eastern Massachusetts and was felt along the eastern seaboard of North America from Nova Scotia to South Carolina (Ebel, 2006). The earthquake was located approximately

40 km ENE of Cape Ann, Massachusetts, and it had a M_w of about 5.9 (Ebel, 2006). The earthquake caused extensive damage in Boston, destroying at least 1,500 and as many as 5,000 chimneys (Whitman, 2002), and it reportedly affected water levels in wells as far away as central and western Connecticut (Thorson, 2001). Crosby (1923) estimated that the 1755 earthquake caused a MMI of IX in Boston, while Ebel (2006) estimated a MMI of VII. Estimates of ground motions in Boston range from 0.08 to 0.12g (Ebel, 2006). Written accounts of damage caused by the 1755 earthquake in Scituate, about 30 km southeast of Boston, reported liquefaction sand boils; these features were investigated using paleoseismic and geophysical techniques, but the studies were not conclusive (Tuttle et al., 2000).

Liquefaction Hazard Mapping

Regional liquefaction hazard mapping projects have predominantly relied on criteria that relate Quaternary surficial deposits to liquefaction susceptibility, taking into account factors such as depositional environment, dominant grain size, and relative age (Youd and Perkins, 1978). This methodology commonly leads to the identification of large regions of susceptible material. Youd and Perkins (1987) discussed how the resulting maps show geologic units that likely contain liquefiable sediments but do not identify the precise location of the liquefiable sediments within the geologic unit. Therefore, it is possible that within a susceptible unit only a small discrete area or areas will actually liquefy during a given earthquake.

Recent liquefaction mapping projects have typically included the concurrent collection of subsurface data to provide more quantitative susceptibility estimates. The subsurface data may include standard penetration test N-values, cone penetrometer (CPT) data, shear-wave velocity (V_s), soil descriptions (including grain-size distributions), stratigraphy, and groundwater measurements. Hitchcock et al. (1999) conducted extensive investigations of liquefaction hazards and produced detailed susceptibility maps in Simi Valley, California, using surficial geologic mapping and analysis of over 1,000 boring logs from a variety of Quaternary deposits. Hitchcock and Helley (2000) collected over 1,600 boring logs for 12 7.5-minute quadrangles in the Santa Clara Valley, California. The boring logs were used to help delineate the top of the Pleistocene deposits, estimate the thickness of Holocene sediments, and determine the thicknesses and time of placement of artificial fills. Monahan et al. (2000) produced relative liquefaction hazard maps for Victoria, British Columbia, from interpretations of stratigraphy derived from over 5,000 boring logs. The hazard classification for the Victoria maps was based on an interpretation of the stratigraphy represented in the boring logs and a detailed analysis of 31 sites. The detailed analysis consisted of a combination of a probabilistic prediction of liquefaction using the Seed and Idriss (1971) simplified approach and a probability of liquefaction severity index, which depends on depth and thickness of the liquefiable materials (Monahan et al., 1998, 2000).

Recently, the California Geological Survey (CGS) has produced seismic hazard zone maps that delineate areas that are likely to contain liquefiable sediments in seismically active areas of the state. The CGS zonation is based on susceptibility evaluations that use geologic criteria and borehole analyses similar to the method used in this study. To date, CGS has compiled Quaternary geology for 113 U.S. Geological Survey (USGS) 7.5-minute quadrangles and has collected and analyzed over 16,000 borehole logs from the greater Los Angeles and San Francisco Bay area (California Geological Survey, 2007).

METHODOLOGY

We applied regional-scale liquefaction mapping criteria based on surficial geology and analysis of geotechnical data to prepare liquefaction hazard maps for the greater Boston metropolitan region. The mapping criteria consisted of three hazard classes (low, moderate, and high), which refer to varying extents of expected liquefaction. Our intent was to provide classes of hazard based on both geologic and geotechnical criteria that account for the variability of geologic materials as well as the distribution of liquefiable materials within an individual geologic unit.

Surficial Geologic Maps

Surficial geologic maps of eight 1:24,000-scale quadrangles (Figure 1) were compiled from existing published geologic maps, where available, and these were augmented with reconnaissance field mapping throughout the study area. High-quality, large-scale, published maps were available for the Norwood (Chute, 1966) and Blue Hills (Chute, 1965) quadrangles, and for portions of the Boston North and Lexington quadrangles (Chute, 1959). Smaller-scale maps of the entire study area were available (e.g., Kaye, 1978; Thompson et al., 1991; and Woodhouse et al., 1991) and provided a first-order base map for use in field checking.

In the mapping, we faced two primary challenges. First, the area is extensively developed; exposure is typically less than one to two percent, and there has been large modification of the land surface throughout the study area. Extensive grading for construction, draining and filling of wetlands and marshes, channeling and diversion of streams and rivers, and modification of river banks have occurred over the past three centuries. These cultural processes often obscure the nature of the underlying deposits, and they occur not only in the densely populated downtown Boston and surrounding urban areas, but also in the outer suburban regions. This difficulty directly affected the level of detail that could be attained in subdividing units during the surficial mapping. Second, previous workers mapping the region over the past century have adopted a variety of classification schemes for the surficial geologic units. This can be attributed to both the development of the science of glacial and Quaternary geology over the past century and also the wide variety of scales of mapping and the various locales that were the focus of the mapping projects.

We addressed these issues by using generalized geologic units based on those defined by Chute (1965, 1966). We divided surficial units into six general units, including glacial drumlins (glacial till), glacial ground and end moraines (glacial till), glaciofluvial deposits (glacial outwash plains, eskers, kames, and kame fields), marsh deposits, beach deposits, and historic artificial fill. These units, while general, group deposits based on common depositional processes, composition, and age, and they are present throughout the study area. In addition, these units form relatively distinct geomorphological terrains and can be identified with confidence on the basis of their surface expression. This allowed us to map geologic units even with the lack of exposures described previously. Admittedly, there is variability of geologic properties within each unit, and in some cases, our morphology-based mapping may have passed over some of the details of the contacts between adjacent map units. However, given the challenges imposed by the issues as described here, we feel that these unit designations do not introduce substantial error into the mapping and provide a good base map for the liquefaction analyses.

Validation and confirmation of our mapping were accomplished by performing reconnaissance mapping of portions of quadrangles with published surficial geologic maps prior to examination of those published maps and then comparing the interpretations between the maps. In all cases, our reconnaissance mapping provided good agreement with the published maps. In addition, published maps from adjacent quadrangles (e.g., the Reading quadrangle; Oldale, 1962) allowed us to check geologic contacts along the quadrangle boundaries. Finally, and importantly, we were able to confirm the map units and refine unit contacts using data from the borehole database and the larger database of borings from the Massachusetts Water Resources Authority.

Geotechnical Borehole Database

Data for this project were acquired from several sources. An electronic collection of data (1,905 borings) was acquired from the Central/Artery Tunnel project in Boston through the Massachusetts Water Resources Authority (MWRA). This database was modified from the original to fit into a standard format. Geologic descriptions varied considerably and were therefore simplified to be more consistent throughout the region, though sample information was not altered. In addition, electronic scanned images of 12,782 boring logs and their location coordinates were acquired from the MWRA. Due to the large number of these data, we selected borings from this set to fill coverage gaps in the other boring databases. Data from 119 of these boring logs were hand-entered into the database. Additional MWRA logs were examined as needed for the surficial geologic mapping and assessment of map unit boundaries. The Boston Society of Civil Engineers (BSCE, 1969) collection of borings was also used as a data source, and 314 borings from the BSCE collection were hand-entered into the database. Finally, for the Cambridge area, 715 borings were collected in and near the Cambridge fill unit along the northern shore of the Charles River. The resulting geotechnical database from all of the aforementioned sources includes 2,963 borings.

Data from geotechnical borings were entered into an electronic database in order to facilitate relational database management and allow for the flexibility of data input. The database includes both general and geologic information gathered from subsurface explorations, such as project and drilling information, date and depth of boring, ground surface elevation, depth to groundwater, depths and descriptions of stratigraphic units and samples, standard penetration test (SPT) N-values, and x-y coordinate values. The soil samples were characterized by soil type (i.e., sand, silt, silty sand, clay, etc.) and a detailed sample description. When available on the original boring log, stratigraphic unit was also associated with individual soil samples. The stratigraphy was characterized by geologic unit and depth to top and bottom of each unit. In some cases, the stratigraphic unit was modified slightly from the original boring log in order to conform to a uniform naming convention.

Quantitative Analysis

Liquefaction susceptibility refers to the relative resistance of soils to loss of strength due to an increase in pore-water pressure caused by ground shaking. The degree of resistance is governed primarily by the soil's physical properties such as grain size, density, and saturation. Zones corresponding to areas of very low to very high susceptibility can be defined based on a liquefaction-triggering threshold analysis using standard penetration test (SPT) data in areas with borehole data, and with criteria based on the deposit's age, texture, and groundwater condition in areas lacking borehole data.

Where borehole data were available, liquefaction susceptibility was quantified according to the adjusted SPT blow count $(N_1)_{60}$ values. This quantitative evaluation of liquefaction susceptibility was based on the Seed-Idriss simplified procedure, which was reviewed and updated in a workshop report summarized by Youd et al. (2001). This procedure calculates soil resistance to liquefaction, expressed in terms of cyclic resistance ratio (CRR), based on SPT data, groundwater level, soil density, percent fines, and sample depth. The groundwater levels in Boston are highly locally variable as a result of sewer systems, dewatering projects, and seasonal variations. We used groundwater data where noted in the boring logs; otherwise, we used a conservative groundwater level at the ground surface. CRR values were compared to cyclic shear stresses generated by the estimated ground motions, expressed in terms of cyclic stress ratio (CSR). Appropriate correction factors for SPT values, and scaling factors for fines content and earthquake magnitude (see following), were applied as suggested in Youd et al. (2001). For each soil sample in the database, a liquefaction trigger level of the peak ground acceleration ($PGA_{trigger}$) was calculated using the simplified Seed-Idriss approach (Youd et al., 2001), as described already, which takes into account depth, saturation, soil type, density, and fines content. A factor of safety (FS) equal to 1.2, which has been recommended to achieve a 20 percent probability of liquefaction (Juang et al., 2002), was used in the calculations. Thus, we calculated the $PGA_{trigger}$ for each soil sample in the database, which allowed us to provide individual classifications of susceptibility. These susceptibility *category values* are distinct from the geologically determined criteria because they are specific to an individual soil sample rather than the entire geologic unit. This allows characterization on two scales: regionally, based on surficial geologic unit, or locally, based on SPT data.

We used a design earthquake of $Mw = 6.0$ for the scaling factors used in the trigger-level calculations to assess the liquefaction susceptibility, based on the historic earthquake record and, specifically, the magnitude of the 1755 Cape Ann event (see previous). In addition, we selected a PGA of $0.12g$ as our design ground motion for determination of liquefaction triggering. Using the 2002 and 2007 (proposed) USGS Probabilistic Seismic Hazard Maps, values for two percent in 50 years peak ground acceleration for Boston match the chosen design value of $0.12g$ (USGS, 2007). For Boston, the Massachusetts Building Code mandates a peak ground acceleration of $0.12g$, which is consistent with the standard of practice.

In regions where subsurface data were not available, we assessed liquefaction susceptibility using geologic criteria as originally defined by Youd and Perkins (1978). These criteria are based on the physical characteristics of a given geologic unit that impact the susceptibility of that unit to coseismic liquefaction, including the depositional environment, age, lithologic composition, grain-size distribution, density, and degree of saturation. While inherently qualitative, classifications using these criteria have been verified through the response of similar geologic units to ground motions during recent large earthquakes, and it is appropriate for regions without available subsurface data.

Liquefaction Hazard Mapping Methodology

In moving from a local, sample-scale assessment of liquefaction susceptibility to a regional-scale susceptibility map, we used a combined approach using both the geologic criteria described already and statistical analysis of the subsurface data. The statistical methodology is described more completely in Baise et al. (2006), and Table 1 summarizes the liquefaction hazard mapping criteria used in this study.

In the development of the liquefaction hazard mapping criteria, an investigation of population statistics was completed for several liquefiable deposits in the study area. The accuracy of the characterization depended primarily on the amount of data available. Using liquefaction probabilities instead of susceptibility categories, Baise et al. (2006) found that the estimated error for the liquefaction probability over a subsurface unit was directly related to the mean value and the number of samples. Susceptibility estimates from population percentages based on $PGA_{trigger}$ values can be misleading when based on a small number of samples from within a given

Table 1. *Hazard criteria used in this study and regional susceptibility mapping criteria based on geologic characteristics of various map units (after Youd and Perkins, 1978).*

Hazard Category	Geologic Criteria (Susceptibility)	Geologic Units	Geotechnical Boring-Based Criteria
High hazard	Modern to Holocene; saturated; abundant cohesionless, uncompacted sediments	Artificial fill Active beach deposits	>20 percent of borings with liquefiable samples
Moderate hazard	Holocene to Pleistocene; saturated; variable amounts of cohesionless, uncompacted sediments	Glaciofluvial deposits Marsh deposits	5 to 20 percent of borings with liquefiable samples
Low hazard	Pleistocene to pre-Pleistocene; non-saturated to saturated; well indurated; cohesive; limited cohesionless sediments	Glacial till (drumlin and ground moraine) Bedrock	<5 percent of borings with liquefiable samples

geologic unit. Therefore, broad regional estimates of liquefaction susceptibility based on limited samples resulted in large levels of estimate uncertainty. If a sufficient sample density is not available, the characterization should rely more heavily on the surficial geology.

The liquefaction hazard criteria presented here do not describe expected deformations resulting from liquefaction (i.e., settlements, lateral spreading, etc.), which would depend on thickness of susceptible unit, depth to susceptible unit, lateral extent of susceptible unit, surface and intra-unit topography, and nearby structures. Rather, the maps produced using these criteria are meant to characterize the spatial extent of liquefiable materials. In addition, the liquefaction hazard mapping is meant for the regional scale and not the site-specific scale. This information can be used to plan detailed explorations for a site to confirm the liquefaction hazard at the site.

SURFICIAL GEOLOGIC MAPPING

Quaternary Geology

The Quaternary geology of the Boston area (Figure 2) is dominated by sediments deposited during and after extensive and repeated Pleistocene glaciations of the area (Kaye, 1982; Barosh et al., 1989; and Woodhouse et al., 1991). Glacial advances deposited till as drumlins and ground moraines, while glacial withdrawal during the late Pleistocene deposited large regions of glacial outwash. The outwash and till together comprise about 75 percent of the surface in the study area. During and after glaciation, coastal processes influenced by the competing effects of crustal isostatic rebound and eustatic sea-level change resulted in a complex distribution of coastal estuarine and tidal marsh sediments. Local beach deposits and tidal estuary deposits developed along active coastal areas and sheltered marshes, respectively. In addition, the Charles River and other smaller rivers (e.g., Mystic and Neponset Rivers) and streams locally deposited sequences of fluvial sands and overbank silt deposits, which line the margins of the river channels and are now often present in the subsurface under the artificial fill units along the banks.

Glacial till is mapped as two separate units: glacial drumlins and ground moraines. Both generally lie directly on the bedrock surface and were deposited below the advancing glaciers or during the melting of stagnant or receding ice (Chute, 1966). These two units were differentiated in the mapping on the basis of their differing and unique morphologies. Drumlins are present throughout the study area, and they have been well described in the literature (e.g., Woodhouse et al., 1991). They occur as round to elliptical hills and highlands generally reaching several tens of meters above the surrounding terrain. Drumlins are often cored by local bedrock highs. Prominent drumlins include several in the Somerville-Medford-Charlestown areas north of Boston, and throughout the Boston outer harbor, where drumlins form many of the harbor islands. Ground moraines are also composed of glacial till but are generally confined to the highlands north, west, and south of Boston. These mapped areas of ground moraine also include extensive areas of bedrock exposure in some of the higher elevations; however, since the areas of bedrock are often discontinuous and occur almost exclusively within the ground moraine unit, we do not break out individual areas of bedrock exposure on the maps. Rather, we note that the ground moraine unit can vary in thickness from several tens of meters to zero, and bedrock exposures can occur in zones of zero ground moraine thickness. Where present, the ground moraine till ranges in thickness from zero up to approximately 40 meters, while drumlin till can reach over 50 meters in thickness (Chute, 1966; Woodhouse et al., 1991).

The till is generally composed of poorly sorted sand, gravel, and cobbles in a clay matrix, and it is generally well consolidated and very dense. Large cobbles and boulders up to 1 m in diameter occur rarely throughout the till, but are often confined to

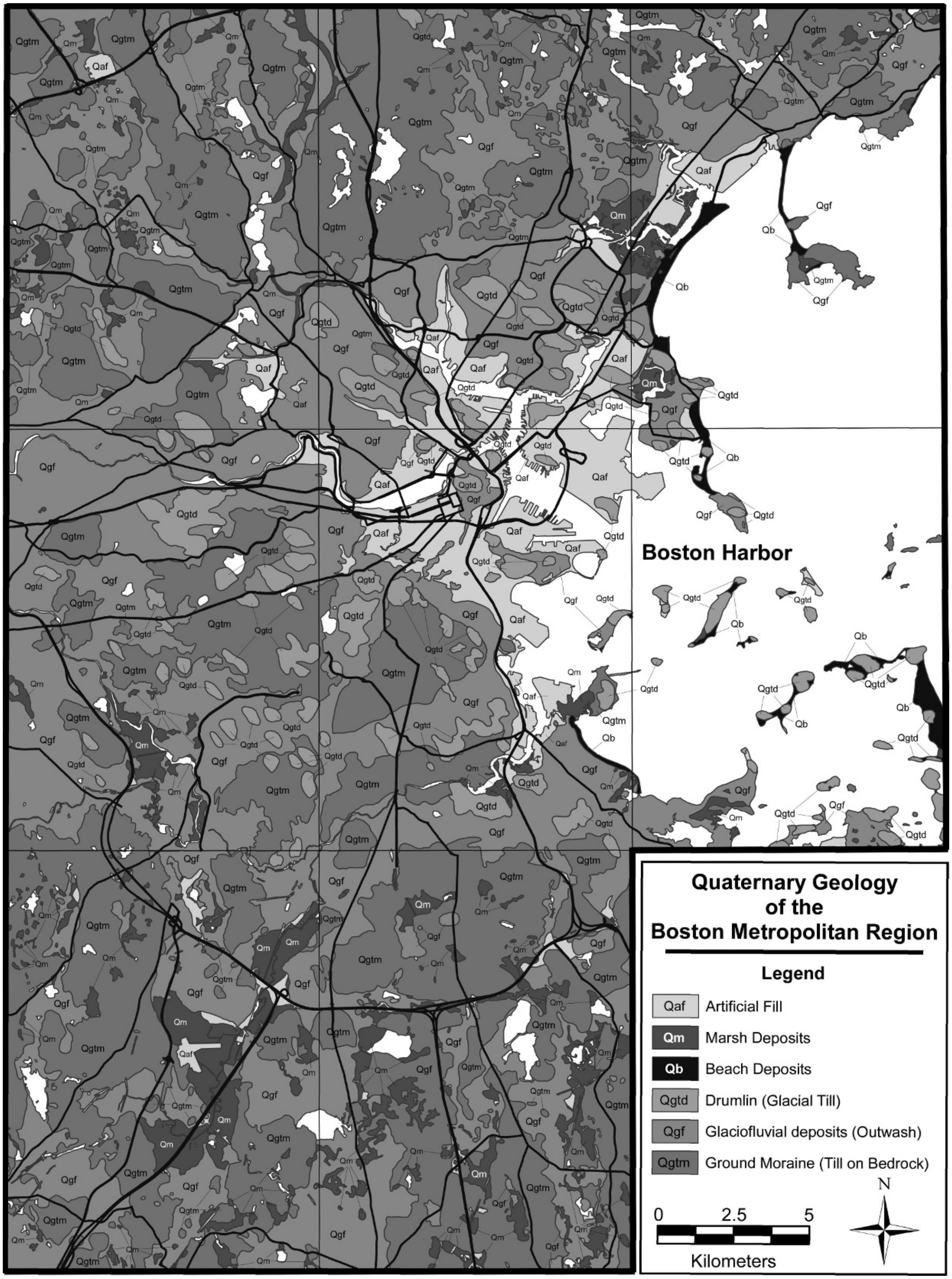

Figure 2. Quaternary geologic map of the Boston metropolitan area, as compiled from published maps and field reconnaissance (see text for references).

the upper 3–4 m (Woodhouse et al., 1991). Silty laminations and well-developed internal structure are often present, in some places highly disrupted and folded by the motion of the glacial ice (Kaye, 1961; Woodhouse et al., 1991). The till ranges in color from brown to yellow to gray. The till was present in 22 borings in the database. SPT blow counts in the till were variable but generally ranged from about 20 to refusal. As a result of their geologic characteristics, both the drumlin till and the ground moraine till are not expected to be susceptible to liquefaction.

The glaciofluvial deposits encompass a variety of deposits formed by the transport of glacially derived materials, either from the glacier front or by subglacial flow, including outwash, eskers, kettles, kame fields, and terraces. These deposits are grouped together for mapping purposes, and they are referred to as glaciofluvial deposits. These are composed primarily of stratified sands and gravels that are heterogeneous in three dimensions as well as in both density and consolidation. The glaciofluvial deposits, with thicknesses of meters to tens of meters, often overlie ground moraine till, and in several locations (e.g., Mystic Lakes–Fresh Pond area), they fill buried bedrock valleys up to about 70 m deep (Chute, 1959). The outwash units range in color from tan to brown and yellow, and they tend to be loose to dense. The glaciofluvial units were encountered in 78 borings, and reported SPT blow counts ranged from five to refusal. The presence of large zones of sand and sandy silt in this unit, as well as zones with relatively low blow counts, indicates that the glaciofluvial units may be susceptible to liquefaction.

Modern marsh deposits are common in the study area and occur both as salt marshes and estuaries along the coastal areas and as freshwater marshes along streams and rivers further inland. Marsh deposits are generally composed of fine sands, silts, and clays, with abundant peat layers. Thicknesses can reach several meters. These units are generally loose, with SPT blow counts generally below 10. Marsh sediments were encountered in 81 samples from 18 borings. Urbanization and suburban sprawl have resulted in a large amount of filling of these regions over the last 75 years; therefore, artificial fill often overlies loose marsh deposits. We consider the marsh deposits to be moderately susceptible to liquefaction based on the presence of discrete layers of saturated, cohesionless sediments between the more organic strata.

Beach deposits represent the sediments deposited by ongoing modern and historic coastal processes. In general, these are composed of sand and gravel and have thicknesses ranging up to several meters. In a small number of borings, extremely high blow counts within the beach deposits indicated the presence of either buried boulders or fill that was subsequently buried by placement of sand during beach reclamation or stabilization. Geologically, the deposition of beach deposits results in loose and often saturated sands; therefore, we argue that beach sands should be mapped as highly liquefiable deposits.

We also recognized several stratigraphic units that occur in the subsurface but do not crop out on the surface and thus could not be included in the geologic maps. These units can be laterally extensive; however, they generally require relatively dense subsurface boring data to map accurately. An example of one of these units is the famous Boston Blue Clay, which underlies much of the Massachusetts Bay area and has been extensively studied in the past because of its impact on deep foundations of buildings in the downtown area. The Blue Clay is a well-bedded deposit of clay, silt, and fine sand formed from the rock flour component of glacial outwash (Woodhouse et al., 1991), and it is not considered to be at risk of liquefaction.

Artificial Fill

The original settlement of Boston was situated on and adjacent to Beacon Hill, a drumlin which formed an island at high-tide (Woodhouse, 1989; Seasholes, 2003). Due to subsequent urbanization, primarily during the mid 1800s to early 1900s, non-engineered artificial fill was placed on the adjacent low-lying tidal marshes, estuaries, and floodplains adjacent to the Boston Harbor and the Charles River (Figure 3). The fill history of Boston has recently been documented using historical maps and documents (Ty, 1987; Seasholes, 2003). Each episode of land reclamation used specific source material and a different filling method; therefore, it is useful to break up the fill unit into subunits, which can then be characterized individually. Figure 4 presents the 10 fill units delineated in this study: Charlestown, Cambridge, Back Bay, West Cove, Mill Pond, East Cove, South Cove, South Bay, South Boston, and East Boston. Although tidal marsh, estuary, and till deposits directly underlie them, these regions are mapped as artificial fill.

In general, the fill layer consists of loose to very dense sand, gravelly sand, or sandy gravel intermixed with varying amounts of silt, clay, cobbles, boulders, and miscellaneous materials such as brick, ash, rubble, trash, or other foreign materials (Ty, 1987; Woodhouse et al., 1991). The source materials include both granular and cohesive material that was obtained from nearby quarries and dumped loosely at sites, generally without sorting or compaction. As a result, properties of the fill layer are extremely variable, and blow counts range up to refusal. In addition, much of the fill is

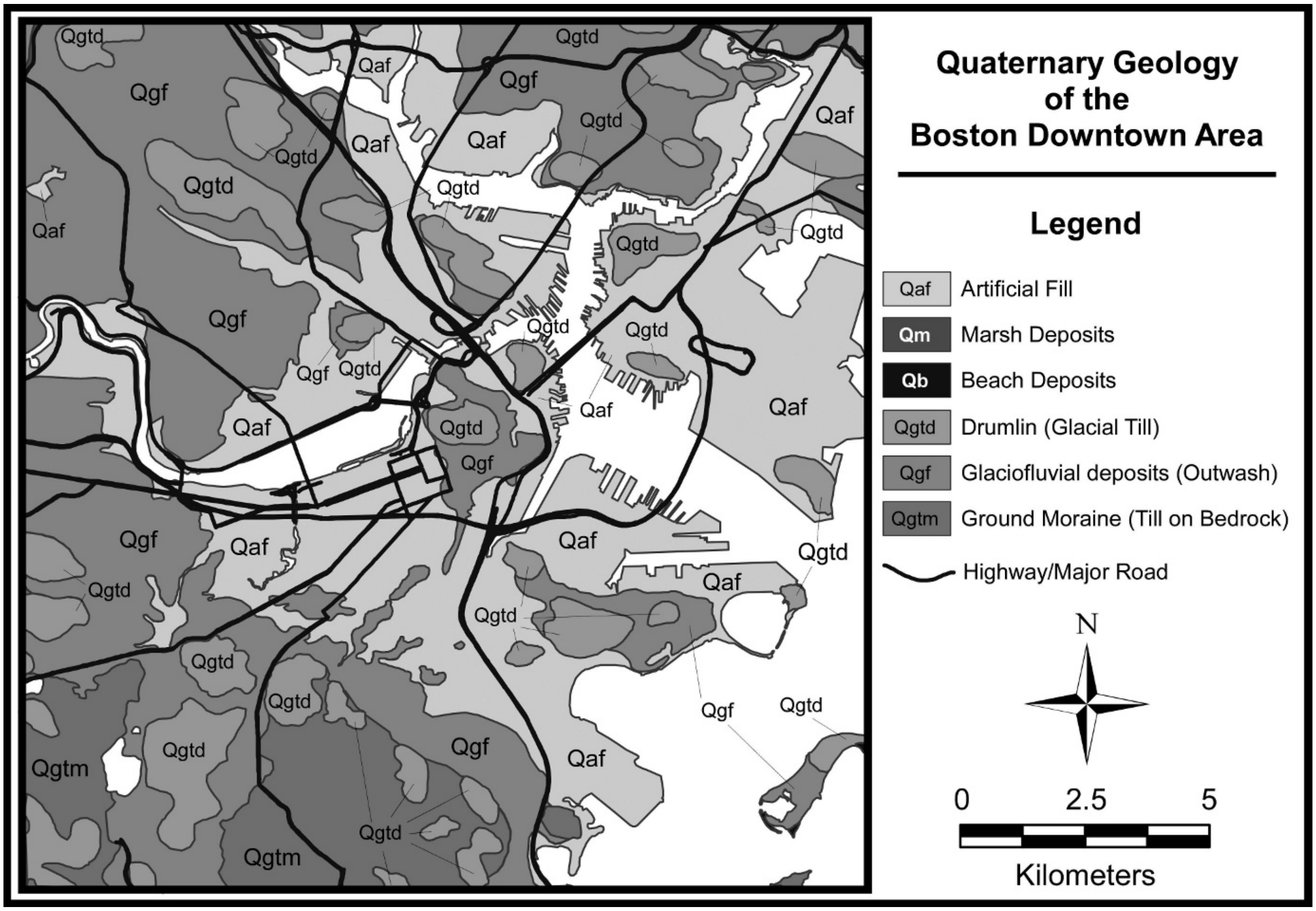

Figure 3. Quaternary geologic map of the Boston downtown area.

saturated as a result of a relatively shallow (although highly variable) groundwater table.

The regions mapped as artificial fill are considered to have the highest liquefaction potential in the Boston area (especially surrounding downtown Boston). If it is saturated and cohesionless, historic (non-engineered) fill is generally considered susceptible to liquefaction because it was loosely placed. Most of the fill underlying newer buildings in Boston is engineered fill rather than the loosely placed historic fill discussed here. Engineered fill, when properly placed and compacted, is usually dense and not susceptible to liquefaction under the modest seismic loading expected in Boston. The historic fill likely remains beneath many historic buildings and roadways.

SUBSURFACE CHARACTERIZATION

Liquefaction Susceptibility

The surficial geology maps (Figures 2 and 3) show the six geologic units: artificial fill, marsh deposits, glaciofluvial deposits, drumlin till, ground moraine till, and beach deposits. Geotechnical data were collected in each of these units; however, the artificial fill unit near downtown Boston and Cambridge was the only geologic unit that was densely sampled. The geotechnical data were only sparsely available over the remainder of the study region. Although we used geotechnical data in all of the geologic units to evaluate liquefaction potential, the susceptibility mapping of all units other than the artificial fill relied more heavily on the geologic characterization, as described next. For the artificial fill unit, a statistical classification was also applied.

In order to use the geotechnical data to ascertain liquefaction susceptibility, all samples in each of the six surficial geology categories were queried from the database. Samples from all units in the boring were included in the analyses. The resulting collections of samples included all soil samples taken within the geographic confines of that surficial geologic unit. Susceptibility analyses were run for these samples using the methodology described previously, and a $PGA_{trigger}$ of $0.12g$ was used as the threshold ground motion for determining failure of each sample. The data and results for each geologic unit are summarized in Table 2, and the distributions of susceptibility

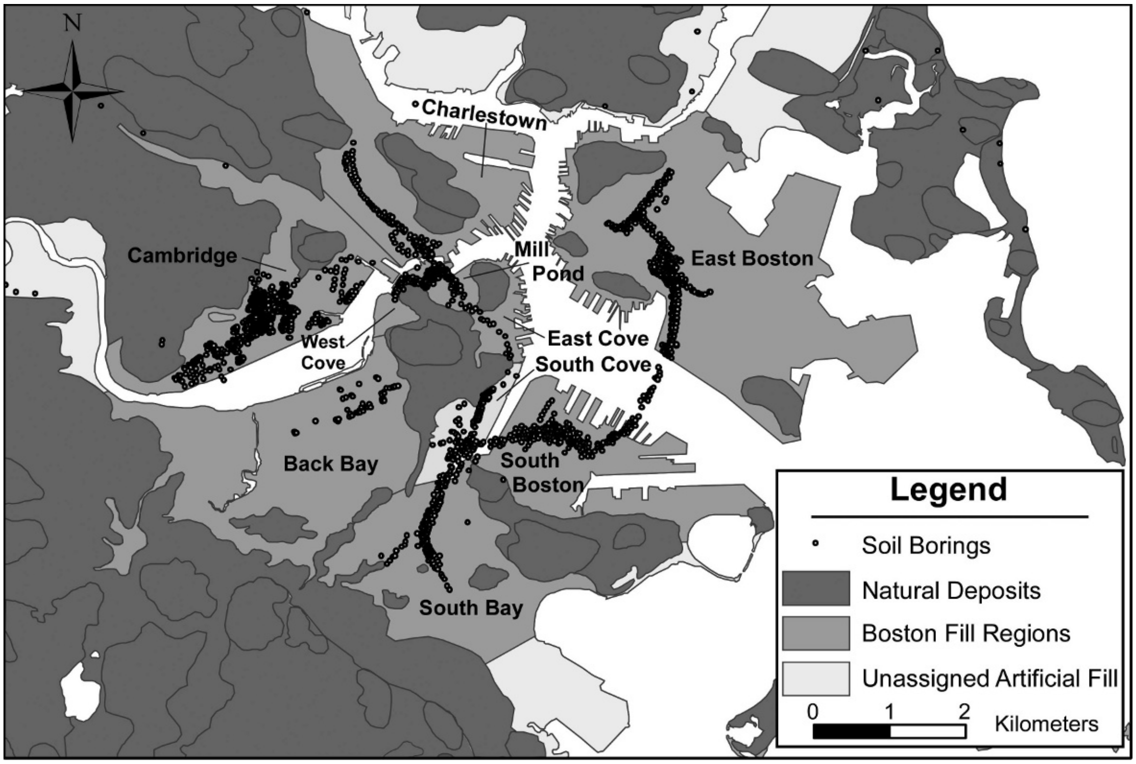

Figure 4. Geographic subunits of artificial fill in the central Boston area.

categories for the three geologic units with susceptible material are shown in Figure 5. As expected, the artificial fill is the most susceptible unit. Marsh deposits also exhibit a relatively high level of susceptibility. The distribution of liquefiable samples in the glaciofluvial deposits exhibits moderate susceptibility.

Very few samples were taken in the drumlin deposit (only 13 samples from six borings across the study area). Based on the depositional conditions of the glacial till that makes up the drumlins, as well as from field observations of exposures of the till, the material is expected to be very dense and not susceptible to liquefaction. Samples from the drumlin deposit confirm this expectation (zero percent liquefiable). Therefore, all drumlin till deposits were categorized as low susceptibility. Similarly, very few samples were taken in the ground moraine till (45 samples from 17 borings). The ground moraine till is generally a thin glacial till deposit over bedrock. These deposits are expected to be dense to very dense. The samples in the ground moraine deposit confirmed the expectation of dense soils; therefore, ground moraines till was mapped as low hazard.

Based on depositional environment and field evidence, the glaciofluvial deposits are composed primarily of interbedded sand and gravel layers with some silt and cobble interbeds of variable density. The results from the geotechnical data are variable: 9 out of 79 borings, or 12 percent, have liquefiable material given the design earthquake. Some borings contain only non-liquefiable samples, while others have several samples that would liquefy for a larger

Table 2. *Distribution of all analyzed samples by geologic unit characterized as susceptible to liquefaction, given a peak ground acceleration of 0.12*g.

	Number of Samples	Number of Borings	Percent of Samples Susceptible to the Design Earthquake (PGA = 0.12g)	Percent of Borings with at Least One Sample Susceptible to the Design Earthquake
Artificial fill	9,898	1,727	7.6	29
Marsh deposits	81	18	7.4	22
Beach deposits***	29	8	0	0
Glaciofluvial deposits	347	79	3.2	12
Drumlin***	13	6	0	0
Ground moraine***	45	17	0	0

***Indicates small sample.

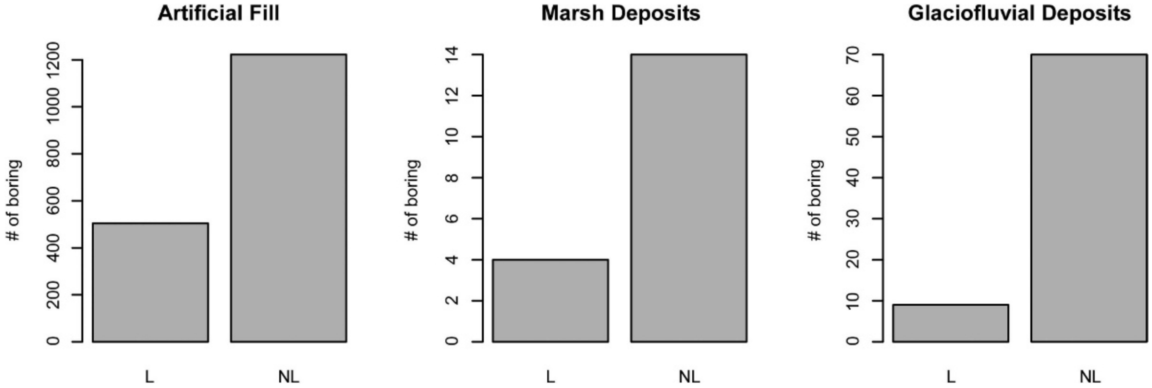

Figure 5. Histograms showing distribution of susceptible (L) and non-susceptible (NL) samples in liquefaction susceptibility categories for the three mapped geologic units with susceptible samples, for M = 6.0 and $PGA_{trigger} = 0.12g$.

earthquake than the design earthquake (PGA > 0.12*g*). The glaciofluvial deposits were mapped as moderate hazard; however, if the design earthquake was altered, the susceptibility could possibly increase. The liquefiable samples within the glaciofluvial units are isolated, and, therefore, we do not expect large, continuous zones of liquefiable materials.

The marsh deposits vary from silty to sandy soils, with abundant organic layers. Most of the soils in the marsh deposits are loose and saturated. The silty and organic-rich soils are not generally liquefiable; however, the sandy soils in these deposits tend to be liquefiable in the design earthquake. In the marsh deposits, 22 percent of the borings contain samples that are susceptible to liquefaction in the design earthquake (Table 2). This is similar to the susceptibility of the artificial fill (see following). The marsh deposits were therefore mapped as high hazard.

The few samples in the beach deposit were not representative of the sandy soils expected in a Holocene beach deposit. After close examination of the 29 samples in the beach deposit, none of the samples was taken in an actual beach deposit. Most were taken within historic artificial fill placed along the seashore, which has been subsequently overlain by beach sand, either placed during beach restoration or deposited naturally, and borings have encountered miscellaneous dense materials. Based on geologic criteria, natural Holocene beach deposits are expected to be loose, saturated sandy deposits and are highly susceptible to liquefaction. The beach deposits were therefore mapped as high hazard.

Overall, 29 percent of borings in the artificial fill contained at least one liquefiable sample. When we subdivided the fill into the individual subregions as summarized in Table 3, the susceptibility was spatially variable depending on the fill and construction history of the area. In several of the fill regions, there were large continuous zones of liquefiable materials (especially West Cove, Mill Pond, Cambridge, Charlestown, and Back Bay). A detail of Back Bay, with the liquefaction categories from the geotechnical borings, is shown in Figure 6. On the other hand, South Boston, South Cove, South Bay, East Cove, and East Boston

Table 3. *Distribution of all analyzed samples for geographically designated artificial fill subunits in central Boston, and percent of samples characterized as susceptible to liquefaction, given a peak ground acceleration of 0.12*g.

Geographic Subunit	Number of Samples	Number of Borings	Number of Liquefiable Samples	Percent of Samples Susceptible to the Design Earthquake (PGA = 0.12*g*)	Percent of Borings with at Least One Sample Susceptible to the Design Earthquake
Back Bay	152	44	25	16	41
West Cove	104	18	14	13	61
Mill Pond	719	116	84	12	46
East Cove	57	13	3	5	15
South Cove	364	121	32	9	18
South Bay	374	130	20	5	14
South Boston	935	220	56	6	21
East Boston	1,453	315	49	3	14
Charlestown	521	110	48	9	35
Cambridge	4,280	638	423	10	40

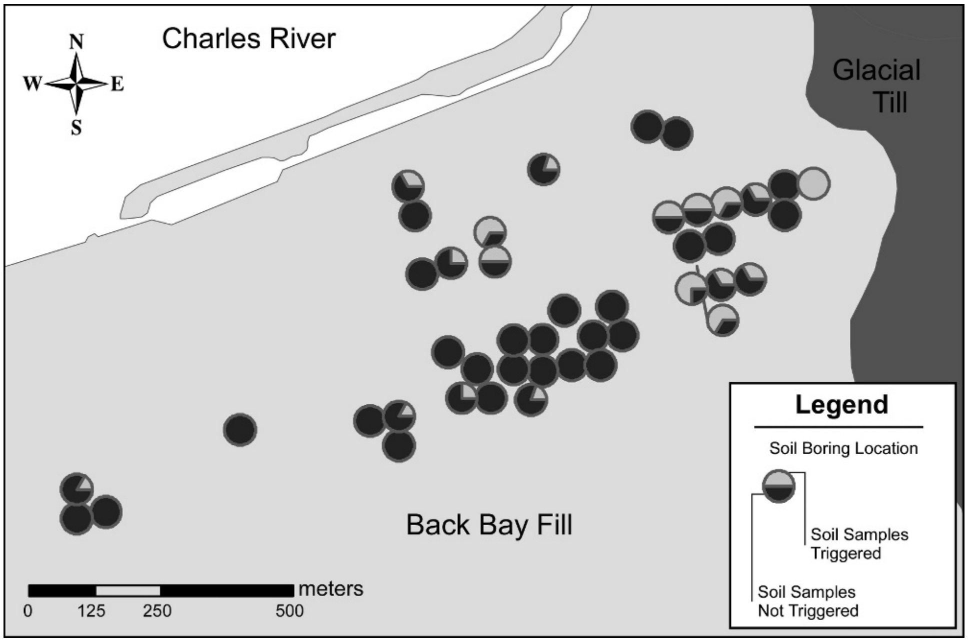

Figure 6. Detail of Boston's Back Bay area showing results of liquefaction susceptibility analyses within the artificial fill. Shaded portions of pie charts represent proportion of different susceptibilities of samples from each boring, for M = 6.0 and $PGA_{trigger} = 0.12g$.

demonstrated a more moderate level of susceptibility, though still higher than any other geologic unit in Boston.

Figure 7 shows the liquefaction susceptibility map for the greater Boston area, while Figure 8 shows the distribution of liquefiable samples in the artificial fill around the Boston peninsula. The Cambridge fill region is highly susceptible to liquefaction for the design earthquake. It should be noted that some regions of fill, particularly those underlying modern highways and developments, have most likely been either removed or adequately compacted during construction and designed to be resistant to liquefaction. However, because we lacked quantitative geotechnical data from most of these site-specific project areas, we mapped them like the other non-engineered fill. Thus, all of the artificial fill regions were mapped as high hazard.

DISCUSSION

In greater Boston, the liquefaction susceptibility of near-surface deposits, both natural and artificial, varies widely across the region. The artificial fill units, marsh deposits, and the beach deposits are mapped as high hazard for liquefaction. The beach deposit characterization is based solely on the surficial geology, since the geotechnical data taken in the beach deposits were sparse and not representative. The artificial fill unit in downtown Boston and in Cambridge has been densely sampled, and 29 percent of borings within the artificial fill contain some susceptible soils. The liquefaction susceptibility is spatially variable across the artificial fill unit and includes many continuous zones of liquefiable material. The marsh deposits and glaciofluvial deposits have 22 percent and 12 percent of borings with some susceptible material, respectively. The glaciofluvial sediments were therefore mapped as moderate susceptibility, while the marsh sediments were mapped as high susceptibility.

The regional liquefaction susceptibility map for Boston and surrounding communities (Figure 7) shows that the highly susceptible regions are concentrated around downtown Boston, where most of the historic artificial fill and underlying marsh deposits are located. Although the artificial fill is mapped as high hazard, the material is highly heterogeneous and varies from very loose to very dense. Complete liquefaction of the entire fill region is not likely to occur; however, large contiguous zones (possibly underlying entire city blocks) are expected. Baise et al. (2006) presented a detailed case study of the susceptibility of the artificial fill along the Cambridge waterfront area, which demonstrated the spatial variability of susceptibility in the fill. While this emphasizes the potential hazard of coseismic liquefaction to structures built in regions of artificial fill, it is important to note that the downtown Boston area has been extensively developed, and it is conventional for large projects to remove the historic fill before construction, or to utilize deep foundations seated in

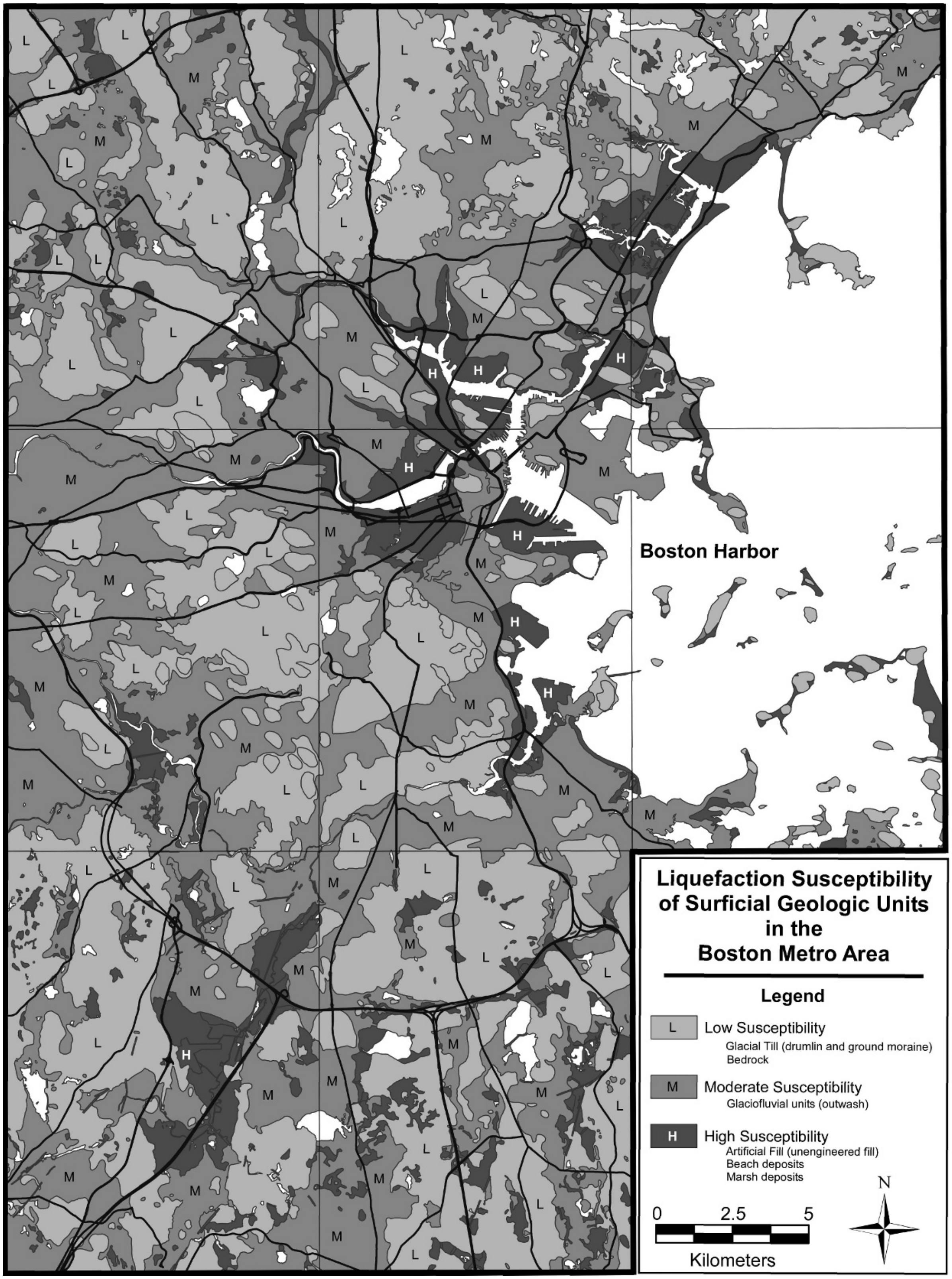

Figure 7. Map showing liquefaction susceptibility of Quaternary geologic units and artificial fill in the Boston region.

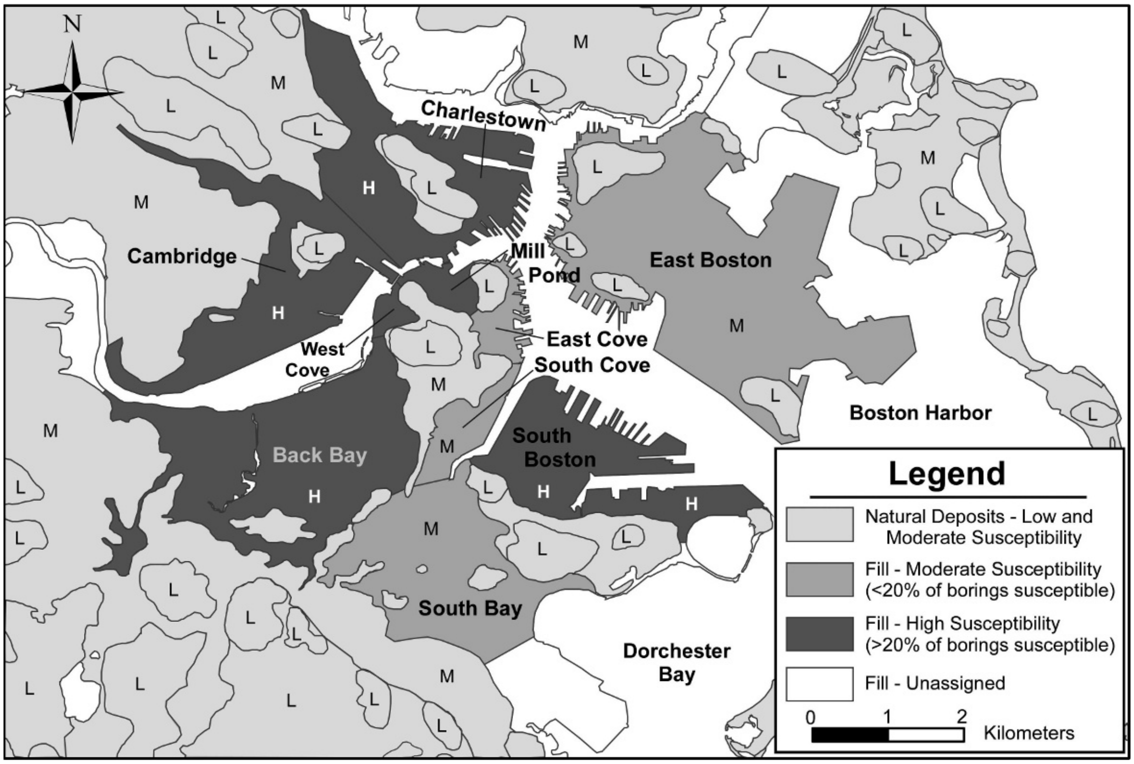

Figure 8. Detail map showing varying liquefaction susceptibility of fill units in downtown Boston.

stable material beneath the fill. Therefore, the hazard to large modern structures is most likely minimal. However, smaller older structures, as well as surface and near-surface roadways and utilities (lifelines) are still likely at risk.

The glaciofluvial sediments were relatively undersampled with respect to the large surface area that they cover. Based on the boring data, this unit is only slightly to moderately susceptible; 9 of 79 borings have at least one sample that is susceptible in the design earthquake. Where observed in several *in situ* exposures throughout the study area, however, the sandy portions of the outwash appear to be loose and unconsolidated, and they often comprise laterally extensive and connected deposits. Given these observations, and assuming that similar conditions exist in the subsurface, it is possible that the boring data do not adequately characterize the susceptibility of this unit, and that significant portions of the glaciofluvial deposits could be at risk for liquefaction. Accordingly, we assigned the unit a susceptibility rating of moderate. Additional boring data from throughout this unit would help to better constrain the potential response of this unit during coseismic ground motions.

Groundwater level has a primary control on the liquefaction susceptibility of a given sediment unit. In our analyses, we conservatively assumed a groundwater level equivalent to the highest reported level or surface groundwater table if none was reported. Seasonal variations in rainfall and snow meltwater can be expected to change groundwater levels; as a result, susceptibility of given samples from the boring database may increase or decrease.

As mentioned already, the susceptibility criteria presented here do not predict expected or possible types of deformation resulting from liquefaction, such as lateral spreading or settlements. These largely depend on the thickness of the susceptible unit, depth to susceptible unit, lateral extent of susceptible unit, surface and intra-unit topography, and nearby structures, and as such, they are local, site-specific effects that must be considered individually. The susceptibility maps produced in this study are meant for the regional scale and not the site-specific scale. This information can and should be augmented with detailed site explorations to confirm the liquefaction hazard at a specific site.

A primary shortcoming of this mapping project was the lack of data in large regions of the study area, particularly in outlying areas. For this study, the most susceptible unit is the artificial fill; therefore, only a limited effort was made to collect geotechnical data over greater Boston. The maps are therefore predominantly based on surficial geology, although the underlying classifications are supported by the quantitative geotechnical data.

CONCLUSIONS

We applied the regional liquefaction mapping criteria presented in Table 1 to prepare liquefaction hazard maps for greater Boston. The mapping criteria consist of three hazard classes (low, moderate, and high) that refer to varying expected extents of liquefaction. The criteria are based on surficial geology and geotechnical data. The intention of the mapping criteria was to provide a hazard class that accounted for the variability of geologic materials and the distribution of liquefiable materials within a regional geologic unit.

We assembled surficial geologic maps for the greater Boston area (Figures 2 and 3). The maps were developed from existing high-quality, large-scale, published maps, smaller-scale maps of the entire study area, as well as field reconnaissance mapping using field exposures and geomorphological interpretation. To complement the surficial geologic maps, we assembled an electronic database of geotechnical data from 2,963 test borings. The geotechnical data included stratigraphy, soil sample description, soil type, groundwater level, and SPT blow count. Although the data are concentrated in the downtown area, the distribution covers the entire study region. The SPT blow count data were analyzed for susceptibility to liquefaction according to standard geotechnical procedures (Youd et al., 2001).

Using the mapping criteria, the surficial geology maps, and the geotechnical data, we prepared liquefaction hazard maps for the greater Boston area. These maps are appropriate for the design earthquake for Boston, MA (M6.0 and PGA = $0.12g$). Artificial fill, marsh deposits, and beach deposits are mapped as high hazard. Marsh deposits are loose deposits of silts and sands. The silty organic soils are not liquefiable, and the sandy soils tend to be liquefiable during the design earthquake. Glaciofluvial deposits are mapped as moderate hazard. Ground moraine and drumlin deposits are mapped as low hazard.

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