FINAL TECHNICAL REPORT

Liquefaction Hazard Mapping in Boston, Massachusetts: Collaborative Research with William Lettis & Associates, Inc., and Tufts University

by:

Laurie G. Baise[1] and Charles M. Brankman[2,3]

with contributions from:

Rebecca B. Higgins[1] and Kevin M. Dawson[1]

[1]Department of Civil and Environmental Engineering
Tufts University
113 Anderson Hall, Medford, MA 02155
phone: 617-627-2211 fax: 617-627-3994
email: laurie.baise@tufts.edu
webpage: http://ase.tufts.edu/cee/faculty/baise/bio.asp

[2]William Lettis & Associates, Inc.
1777 Botelho Drive, Suite 262, Walnut Creek, CA 94596
phone: 925-256-6070 fax: 925-256-6076
email: brankman@lettis.com
webpage: http://www.lettis.com

[3]now at: Department of Earth and Planetary Sciences, Harvard University
20 Oxford Street, Cambridge, MA 02138
phone: 617-495-0367 fax: 617-495-7660
email: brankman@fas.harvard.edu
webpage: http://structure.harvard.edu

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ABSTRACT

Liquefaction Hazard Mapping in Boston, Massachusetts: Collaborative Research with William Lettis & Associates, Inc., and Tufts University

Laurie G. Baise[1] and Charles M. Brankman[2,3]

[1]*Department of Civil and Environmental Engineering, Tufts University, 113 Anderson Hall, Medford, MA 02155; phone: 617-627-2211; fax: 617-627-3994; email: laurie.baise@tufts.edu*

[2]*William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek, CA 94596; phone: 925-256-6070; fax: 925-256-6076; email: brankman@lettis.com;*

[3]*now at: Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138; phone: 617-495-0367; fax: 617-495-7660; email: brankman@fas.harvard.edu*

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We have completed a two-year detailed study to characterize the surface and subsurface distribution of potentially liquefiable sediments and artificial fill in the City of Boston, Massachusetts funded by the NEHRP program. The study encompasses eight USGS 7.5 minute quadrangles that include the downtown Boston area and surrounding communities. This area is a highly populated urban and industrial center and has experienced several large historic earthquakes of M>6.0 (e.g. 1727 and 1755). Much of the study area, especially in the downtown Boston area, is underlain by extensive regions of non-engineered artificial fill that, when saturated, are susceptible to liquefaction during seismic loading. In addition, 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 a low susceptibility to liquefaction.

We use a multi-disciplinary approach that includes Quaternary geologic mapping and geotechnical analyses to determine liquefaction susceptibility, as well as probabilistic and geostatistical techniques to understand the variability of the geologic units. We compiled a digital database of 2963 geotechnical boreholes in order to characterize the liquefaction susceptibility of subsurface units. These data were complimented with published geologic maps,

aerial photographic interpretation, and soil stratigraphy from another 12,000 geotechnical boring logs. Liquefaction triggering threshold levels of ground motions were determined using the borehole data. The spatial uncertainty of the assembled database was quantified with geostatistical techniques, using a semi-variogram to characterize the spatial correlation and Kriging to interpolate at unsampled locations.

This research directly addresses the External Research Program Announcement for 2002, Element I (Products for Earthquake Loss Reduction), which states that products are needed to "quantify shaking amplification and susceptibility to liquefaction", and to "compile new and upgrade existing data that provide input information for seismic hazard maps." The study provides data needed to effectively manage liquefaction hazards in the Boston area, and thus contributes to the USGS and FEMA loss reduction efforts in the northeast United States. The digital maps and geologic database generated by this research will assist in characterizing seismic hazards and mitigating risks, and will provide valuable information for urban planning.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

Digital files in pdf format are included in the enclosed CD-ROM

1.0 INTRODUCTION

In this investigation, we assess the susceptibility to liquefaction of natural sediments and areas of artificial fill in the Boston, Massachusetts metropolitan area. The primary goal of the study is to combine surficial geologic mapping with borehole data to characterize the surface and subsurface distribution and geotechnical properties of potentially liquefiable sediments and artificial fill in the City of Boston, Massachusetts. To develop these maps, existing surficial geologic maps were augmented with field reconnaissance mapping to provide a base for assessing the properties of the geologic units. An extensive digital borehole database, composed of approximately 2963 borings from throughout the study area, was compiled to provide data on the subsurface properties of the geologic units. The subsurface properties, including standard penetration test blowcounts, soil type, and estimated fines content, were used to determine liquefaction susceptibility of each individual sample in the database. Local groundwater conditions were utilized in the susceptibility analyses. The results of the liquefaction analyses are also included in a GIS database, which facilitates distribution and use of these results by interested academic researchers, private parties, and local, state and federal governmental agencies.

The study area encompasses eight 1:24000-scale quadrangles in the metropolitan Boston region, and includes the downtown Boston area and surrounding communities as shown in Figure 1. As Boston is located in a region of historic seismicity, with several historical events of M6.0-6.5 (e.g. 1727, 1755), a need therefore existed for an in-depth study of the liquefaction hazard of the Boston area, to characterize the hazard and provide information to communities for improved planning and mitigation strategies. Much of this area 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. These unconsolidated granular materials are potentially susceptible to liquefaction during large earthquakes. To our knowledge, however, no comprehensive characterization of the geotechnical properties of these units, or detailed maps of liquefaction susceptibility, exists for the greater Boston area.

In this report, in addition to the regional susceptibility maps, we will discuss how the collection of boring logs can facilitate a more detailed characterization of susceptible units to liquefaction. In Boston, we have collected and compiled almost 3000 boring logs in a digital relational database. The majority of these borings are located in regions of non-engineered artificially filled land near downtown Boston. We then performed two detailed studies to determine how to best use geotechnical information to make regional liquefaction hazard maps. For the first detailed study, we will focus on the Cambridge area along the Charles River that samples historic fill as well as the underlying Holocene sand deposits. We have over 700 borings in this study area. For this study, we use statistical, probabilistic, and geostatistical methods to characterize the extent of liquefiable deposits over the region. We will then look at a second case study where we characterize the different fill units in Boston using over 1900 borings. The second case study will use three-dimensional characterization to locate zones of liquefiable material in three-dimensions. The overall goal of these case studies was to develop statistical methods to characterize the spatial extent of liquefaction susceptibility for regional geologic units.

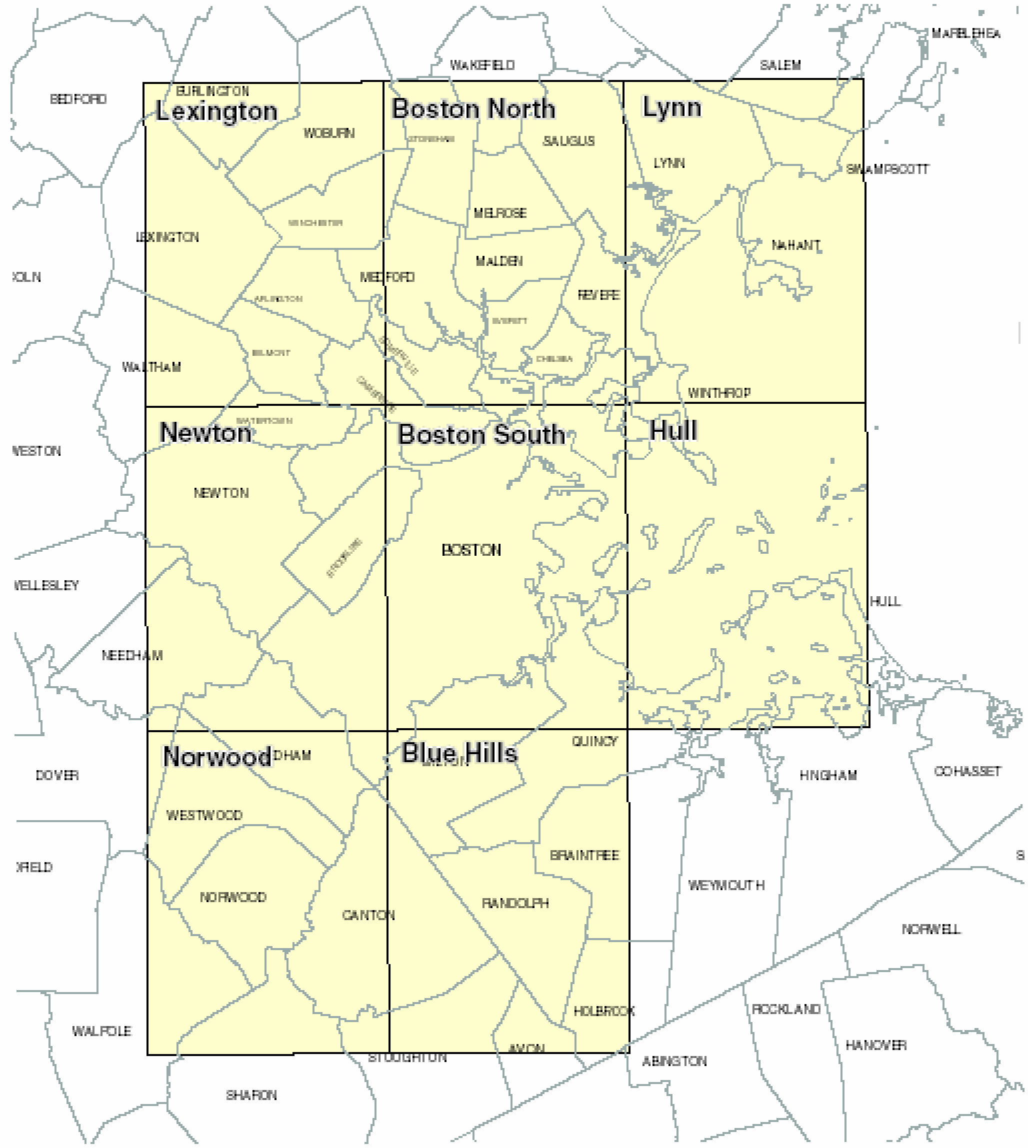


Figure 1. Location map of study area, showing quadrangle outlines and names.

2.0 BACKGROUND

Liquefaction-related ground failures during large earthquakes have historically caused extensive structural and lifeline damage in urbanized areas around the world. Recent examples of these effects include damage produced during the 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Turkey and Taiwan, 2001 Indian and Nisqually earthquakes. These and other historical earthquakes show that the occurrences of coseismic liquefaction, and thus the distribution of liquefaction-related damage, is generally restricted to areas that contain low-density, saturated, near-surface granular sediments and that are in regions with the opportunity for coseismic ground motions to exceed a specified threshold level. Coastal urban areas with large areas of artificial fill have historically suffered particularly heavy damage from liquefaction-related ground failure during earthquakes. For example, San Francisco experienced liquefaction-related failures during the 1906 San Francisco earthquake as well as the 1989 Loma Prieta earthquake. The liquefaction-related damage was especially evident in areas of artificial fill (i.e. the Marina District, south of Market, Treasure Island, and Oakland Airport). In addition, documentation of localized liquefaction features produced by the 2001 Nisqually earthquake in former tidal flats that had been covered by artificial fill near Seattle appear to confirm the vulnerability of these older fills.

The original settlement of Boston was situated on Beacon Hill, a high-tide island which prospered as a result of the natural harbor, the protection from enemies, and a good fresh water supply (Woodhouse, 1989). However, the present coastline is quite different than the original coastline, after centuries of filling of tidal flats to create more land for development. According to Ty (1987), more than 1/3 of the surface area of Boston and Cambridge is artificial fill. Much of this fill consists of non-engineered loose, saturated cohesionless sediments (Johnson, 1989; Ty, 1987; Seasholes, 2003) and therefore may present a significant liquefaction hazard in large earthquakes.

Four major historic earthquakes have occurred in the vicinity of Boston and are documented in the written record: 1638, 1663, 1727, and 1755. Historical accounts of these events indicate that ground motions sufficient to trigger liquefaction were experienced in the Boston area. Of these, the best documented are the 1727 and 1755 Cape Ann events. In the 1727 event, the most significant effects were felt in Newbury, Massachusetts (approximately 56 km northeast of Boston) with a reported Modified Mercalli Intensity (MMI) of VII and an estimated moment magnitude of 5.2 (Ebel, 2000). The MMI for Boston during this event was reported to be V to VI. Reports in Newbury described "… in some places (in the lower ground about three miles from my house) the earth opened and threw out some hundred loads of earth of a different color from that near the surface…" (Rev. Mathias Plant, minister at Newbury, 1727). Crosby (1923) estimates the MMI in Boston for the 1755 earthquake was at IX and for the 1663 earthquake at VIII. Written accounts of damage caused by the 1755 earthquake in Scituate, Massachusetts reported: "…there were several chasms or openings made in the earth, from some of which water issued, and many cart-loads of a fine whitish sort of sand…" (John Winthrop, 1756). One important difference between the potential damaging effects of these historic earthquakes and the hazards of future earthquakes is that in the 18th century, most of the city of Boston was on natural land (Crosby, 1923), whereas today significant portions of Boston are built on areas of nonengineered artificial fill.

Recent paleoseismic studies in Newbury and Scituate have been conducted in order to locate and evaluate liquefaction events (Tuttle and Seeber, 1991; Tuttle et al., 2000). In the earlier study, sand dikes and sills in glaciomarine sediments were observed in two instances in Newbury, Massachusetts approximately 56 km northeast of downtown Boston (confirming early witness reports of ground failure typical of liquefaction. In the later study, a site in Scituate, Massachusetts (approximately 27 km southeast of Boston) was investigated to identify liquefaction features resulting from the 1755 event. The soils at the site were glacial outwash deposits and Pleistocene delta deposits. The Scituate study was unable to find past evidence of liquefaction due in large part to restrictions at the site.

Despite the presence of potentially susceptible geologic units and the historical accounts of strong ground shaking associated with earthquakes in the Boston area, surprisingly little research has focused on liquefaction hazards in the Boston area. The only identified liquefaction susceptibility maps for Boston were created in the mid-1980s as a result of a USGS-funded project conducted at MIT. The project consisted of three components: (1) the surficial geology of Boston (Hawkes, 1987), (2) the history and character of fill in Boston (Ty, 1987), and (3) liquefaction of the greater Boston region (Hashash, 1988).

Ty (1987) provides a detailed overview of the sequence of filling in Boston, including a summary of source regions and filling methods. He identified the categories of fill material used in Boston as sand and gravel from the hills on the Boston peninsula and quarries in outer areas, as well as silt and clay from the Charles River and the Boston Harbor (Ty, 1987). Liquefaction hazard maps were developed for a portion of the Back Bay of Boston using a limited existing borehole database (BSCE, 1961) to establish the subsurface conditions and the liquefaction susceptibility analyses used at the time (Hashash, 1988). Liquefaction hazard maps of Lowell and Newburyport were also developed as well as simplified maps of eight USGS quadrangles north of Boston (Hashash, 1988). These studies did not address the liquefaction susceptibility of the entire city of Boston, but rather a small subregion using only a limited subsurface data set. In addition, the product maps are of a very small scale and not registered to any existing USGS quadrangles or other useful reference maps. Thus, while these studies provide a framework and introduction for more detailed liquefaction related work, they are general in nature and do not represent the level of detail that is possible in the current project.

In terms of general earthquake hazard in Boston, a team of researchers performed an unpublished case study of earthquake hazard in Boston during the development of the HAZUS software (Whitman, personal communication, 2004). HAZUS is a GIS software package sponsored by FEMA that examines regional loss estimation for natural disasters. The Boston study included a liquefaction hazard assessment, which was based on engineering judgment combined with surficial geologic maps. Unfortunately, the results of this study were not published and are not publicly available, so a direct comparison between that study and our own is not possible. In addition, two recent studies on ground amplification in Boston were recently published (Ebel and Hart, 2001; and Hayles et al., 2001). The research has focused on soil amplification in downtown Boston rather than liquefaction hazard. Work by the authors has included analysis of soil borings in GIS.

Regional liquefaction hazard mapping projects have predominantly relied on criteria that relate surficial geology to liquefaction susceptibility (Youd and Perkins, 1978). Geologic units are identified by their age and depositional environment and then characterized in terms of their susceptibility. This methodology leads to the identification of large regions of susceptible material. As Youd (1991) discusses, the resulting maps show geologic units that likely contain liquefiable sediments but do not identify the exact location of the liquefiable sediments within the geologic unit. Therefore, within a susceptible unit, maybe only a very small area will actually liquefy given an earthquake.

As liquefaction hazard mapping projects proliferate around the country and the world, the mapping method has remained relatively constant. Most of the existing liquefaction susceptibility maps are based solely on geology. For example, the liquefaction susceptibility maps for the San Francisco Bay Area provided on the ABAG website are a direct interpretation of the susceptibility of surficial deposits based on surficial geologic mapping of the region (Knudsen et al., 2000). Currently, many liquefaction mapping projects include the concurrent collection of subsurface data to provide more quantifiable data for the susceptibility estimate. The subsurface data may include standard penetration test N-values, cone penetrometer data, soil descriptions (including grain size distributions), stratigraphy, and groundwater data. Generally, a scattered sample of subsurface data is collected in the susceptible unit and used to characterize that unit; however, the maps are still primarily based on surficial geology. Recent studies in Victoria, British Columbia; the Rio Grande Valley; Seattle, Washington; Ventura and Santa Clara Counties, California; and Memphis and Shelby Counties, Tennessee have used subsurface test borings logs to supplement the characterization of susceptible deposits. Hitchcock and Helley (2000) collected over 1600 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 the thickness and ages of artificial fills. The top of the Pleistocene deposit could be identified in the borings logs by a notable increase in SPT density, and changes in color and texture of soil. The interpretation of boring logs was secondary information used to refine the surficial geologic map and the liquefaction assessment was derived from the resulting surficial geology. Broughton et al. (2001) also use boring logs in their analysis of liquefaction susceptibility maps for Memphis and Shelby Counties, Tennessee. Their maps were produced strictly by geologic methods and the analysis of boring logs (following the Seed and Idriss (1971) simplified approach) was used to verify the results in a qualitative way.

When regional liquefaction hazard mapping is attempted in a city, numerous locations of subsurface data are often available. Rather than perhaps 10 subsurface borings over a square mile, often thousands of subsurface borings are available. With a dense array of subsurface data, the characterization of units becomes more complete. The relative liquefaction hazard maps produced for Victoria, British Colombia also depended on the interpretation of stratigraphy derived from over 5000 boring logs (Monahan et al, 2000). 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 only 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 and 2000). Six stratigraphic units were characterized using anywhere from 1 to 11 borings. The susceptibility classifications took into account the variability of investigated sites by setting a range of susceptibility rather than an absolute value: medium to very high or high to very high.

Susceptible units to liquefaction are usually of Holocene age and include artificial, non-engineered fill, alluvial deposits, beach deposits, fluvial deposits, and floodplain deposits. Each of these depositional environments generally produces a loose deposit of sand. One of the differences between these deposits is the uniformity. Floodplain deposits usually produce broad expanses of loose sand. These deposits can therefore be characterized by a few well spaced geotechnical boring logs. Holzer et al. (1994) were able to map the extent of a lateral spread in a floodplain deposit using CPT and SPT data from 11 SPT borings and 25 CPT borings. The area under investigation was approximately 5 square km. The uniformity of the deposits allowed for an accurate characterization of the liquefied materials. On the other hand, Holzer et al. (1999) demonstrated that alluvial deposits are heterogeneous and spatially variable and therefore do not lend themselves to detailed surficial geologic mapping. Therefore, how we set out to characterize susceptible deposits should depend on the depositional environment.

One issue that has been raised by several researchers (Iwaskai et al., 1978; Ishihara, 1985; Youd and Perkins, 1987; Toprak and Holzer, 2003) in liquefaction hazard maps is whether the map represents the likelihood of liquefaction or the potential for damage as a result of liquefaction. Iwasaki et al. (1978) developed the liquefaction potential index (LPI) to assess the potential for liquefaction to cause damage to foundations. The LPI relates the thickness of the liquefiable layer, the proximity of the liquefiable layer to the surface, and the calculated factor of safety to an index for damage. The LPI is an extremely useful measure; however, it is difficult to put into practice because it relies on an integration of factor of safety over a depth of 20 m. The integration is difficult when sampling intervals are not evenly spaced. Ishihara (1985) developed a simpler relationship that relates the depth to the liquefiable layer and the thickness of the liquefiable layer to the occurrence of ground damage. In another attempt to provide a measure of damage, Youd and Perkins (1987) proposed the liquefaction severity index (LSI) that could be used to assess the severity of damaging ground effects resulting from a liquefaction event. Severity is a local measure of severity of ground deformations. They developed an empirical relationship that related LSI (probable maximum ground deformations) to earthquake magnitude and source to site distance. The LSI is a regional measure and is related to the general maximum severity (i.e. excluding anomalous high severity values). The LSI is normalized for a specific geologic context and therefore does not include specific subsurface information.

Toprak and Holzer (2003) performed a field assessment of the LPI in order to assess the LPI value that corresponds to surface manifestations of damage. They found that LPIs over 5 corresponded to surface damage. They also found that the cutoff between LPIs that corresponded to liquefaction versus no liquefaction was not a clean break and depended on the geologic environment. Therefore, they used probability methods to quantify the probability of liquefaction for a given LPI. In addition, Holzer et al. (2002) have completed liquefaction hazard maps for Alameda, Berkeley, Emeryville, Oakland, and Piedmont, California using LPI based on 290 cone penetrometer tests. Holzer et al. (2002) applied the LPI to regional mapping by assigning approximate percentages of affected area for each geologic unit. The mapped percentages were found by finding the percentage of LPI values over 5 for each geologic unit.

We set out to provide more information on the likelihood of liquefaction in a susceptible unit using probability methods and spatial statistics and a dense collection of geotechnical data. Regional liquefaction susceptibility maps will never provide detailed enough information for absolute susceptibility at a site level and are not meant to, but a more thorough characterization than currently used will lead to a more accurate assessment of risk. We propose a new method of regional liquefaction hazard mapping that includes estimates of the spatial extent of liquefaction and the distribution of liquefiable soils. Our proposed method is based on two case studies in Boston where dense collections of subsurface test borings were collected to characterize potentially liquefiable materials.

3.0 METHODOLOGY

In this study, we follow the general procedure developed and tested in previous liquefaction susceptibility mapping projects in California with modifications to better incorporate the variability of geotechnical data in the hazard estimate (as discussed above). Our methodology emphasizes interpretation of surficial geologic mapping, augmented by quantitative evaluation of borehole data, as the basis for assessing liquefaction susceptibility. The quantitative evaluation of borehole data includes statistical, probabilistic, and geostatistical techniques to assess the extent of liquefiable materials within a regional geologic unit. Geologic maps enable extrapolation of sparsely distributed boring log data, thus providing a means to consistently map liquefaction hazards over large areas. Our goal is to provide an estimate of the extent of liquefiable materials within a specific geologic unit as part of the hazard rating. Our compilation of existing mapping, as well as our own field mapping, is done in a Geographic Information System (GIS) environment to provide a regionally consistent map base, and to allow for the addition of future, more site-specific geologic and geotechnical data should they become available.

Because lithologic and engineering properties of sediments can vary significantly both laterally and with depth, it is necessary to integrate surface and subsurface data to realistically depict three-dimensional variations in liquefaction susceptibility on two-dimensional maps. The accurate extrapolation of these properties away from known data points (borings) is an additional challenge; boring data are unevenly distributed across the study area, and the natural variability of soil properties within a given geologic unit must be accounted for. We approach this issue with a combination of two techniques. First, geologic units are defined on the basis of surficial mapping, and interpreted based on the likely source(s) of deposits, the environment(s) of deposition, and the relative ages of the deposits. This allows for a first-order division of soils into units with likely similar geologic and geotechnical properties. The procedure for compilation of the surficial geologic maps is discussed in section 3.1 below. Secondly, we employ geostatistical techniques to assess the natural variability of properties within the geologic units, and develop procedures for accurately extrapolating away from known data points and for classifying the susceptibility of units based on statistics. The procedure for incorporating geotechnical boring data using statistical methods is discussed in sections 3.2 and 3.3 below. The primary layer of concern in Boston is the non-engineered artificial fill, a highly heterogeneous layer; therefore, the proposed statistical methods are necessary for adequately characterizing the hazard.

3.1 Surficial geologic maps

Surficial geologic maps of eight 1:24000-scale quadrangles (Figure 1) were compiled from existing published geologic maps, where available, and 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. Thompson et al., 1991; Woodhouse et al., 1991; Kaye, 1978) and provided a first-order basemap for use in field checking.

In the mapping, we faced two primary challenges. First, the area is extensively developed, with exposure typically less than 1-2% and large modification of the land surface throughout the study area. Grading for construction, draining and filling of wetlands and marshes, channeling and diversion of streams and rivers, and modification of river banks has occurred over the past four centuries. These cultural processes often obscure the nature of the underlying deposits, and occurs not only in the densely populated downtown Boston and surrounding urban areas, but also notably 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, workers mapping the region 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 with the wide variety of scales of mapping and the various locales that were the focus of the various mapping projects.

For our maps, we addressed these issues by using general geologic units based on those defined by Chute (1965, 1966). We divide surficial units into six general units, comprising glacial drumlins (glacial till), glacial ground and end moraines (till), glacio-fluvial 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 are present throughout the study area. In addition, these units form relatively distinct geomorphological terrains and can be identified with high confidence on the basis of their surface expression. This allowed us to map geologic units even with the lack of exposures described above. Admittedly, there is variability of geologic properties within each unit, and in some cases our morphology-based mapping may pass over some of the details of the contacts between adjacent map units. However, given the challenges imposed by the issues described above, we feel that these unit designations do not introduce substantial error into the mapping and provide a good basemap for the liquefaction analyses.

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

As noted above, our mapping was done in a GIS environment. Our primary mapping was done at a scale of approximately 1:24000. However, presentation of the maps in the GIS allows for the display of the data at any scale. We caution that use of the maps at scales larger than at what the data were collected may result in inaccuracies at the site-specific scale. Use of the digital database produced by this study should therefore not violate the spatial resolution of the data. Resolution higher than that of the original mapping is illusionary and enlargement of the maps to larger scales will not yield greater detail.

3.2 Liquefaction Calculations

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 are 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 for areas lacking borehole data.

When borehole data were available, liquefaction susceptibility was quantified according to the adjusted SPT blow count $(N_1)_{60}$ values. The quantitative evaluation of whether soils in this study are susceptible to liquefaction 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, etc. We used groundwater data from the boring log when available; otherwise we used a constant regional groundwater level. CRR values were compared to cylic shear stresses generated by the estimated ground motions, expressed in terms of cyclic stress ratio (CSR). Appropriate correction factors for SPT values were applied according to the values suggested in Youd et al. (2001). Appropriate scaling factors for fines content, magnitude were used as suggested by Youd et al. (2001).

In order to summarize the peak ground acceleration (PGA) that will trigger liquefaction at a given soil sample location, a trigger level ($PGA_{trigger}$) was calculated using a Factor of Safety (FS) equal to 1.2. The trigger value was then categorized as very high, high, moderate, low, or very low susceptibility as in terms of categories 1 through 5 (see Table 1). As a result, each soil sample with a blowcount value has an associated trigger value for liquefaction. The trigger values take into account depth, saturation, soil type, density, and fines content by way of the simplified Seed and Idriss approach (Youd et al., 2001). These susceptibility *category values* are different than the geologic criteria because they are specific to an individual soil sample rather than the entire geologic unit. Therefore, liquefaction susceptibility can be assessed on two scales: regionally based on surficial geologic unit or locally based on SPT data. A major goal of this project is to develop a methodology to incorporate both types of data in a single map.

Liquefaction Susceptibility Category		**Criteria**
Very Low	1	No liquefaction
Low	2	$0.3g < PGA_{trigger}$
Moderate	3	$0.2g < PGA_{trigger} < 0.3g$
High	4	$0.1g < PGA_{trigger} < 0.2g$
Very High	5	$PGA_{trigger} < 0.1g$

Table 1. Liquefaction Susceptibilty Categories for soil samples based on peak ground acceleration trigger values ($PGA_{trigger}$)

We use the trigger levels to assess the liquefaction susceptibility initially so that we are not constrained to a specific earthquake source model. For Boston, the Massachusetts Building Code mandates a peak ground acceleration of 0.12 g for Boston which is consistent with the standard of practice. As discussed in the Background section of this report, the seismic hazard work in Boston has been limited and a source model is not well defined; therefore, we felt that the code value of 0.12 g was the appropriate design peak ground acceleration value for Boston. Because the trigger levels have been calculated, a more sophisticated source model like the USGS Probabilistic Seismic Hazard Maps could be implemented in the future. Incorporating the USGS Probabilistic Seismic Hazard Maps peak ground accelerations as source information for the liquefaction analysis would be necessary if the results were to eventually become a part of a fully probabilistic analysis of hazard. According to the 2002 USGS Probabilistic Seismic Hazard Maps, the 2% in 50 years and 10% in 50 years peak ground acceleration values in Boston bracket the design value, 0.12 g.

3.3 Statistical methods

We use statistical methods to combine geotechnical data (SPT data and local liquefaction susceptibility category values) with the more regional geologic criteria for liquefaction susceptibility. First, we treat a delineated geologic unit as a population that is sampled by geotechnical borings. Each boring generally takes multiple samples resulting in a clustered sample. We use statistical methods first to characterize the population statistically and probabilistically and second to determine how many borings one needs to accurately characterize the unit. Standard statistics (mean, standard deviation, etc) as well as histograms are used to estimate the population variability of SPT blowcounts and liquefaction susceptibility category values. Next, we use probabilistic methods to characterize the susceptibility in terms of probability. SPT blowcounts can be characterized by a lognormal distribution. The parameters of the lognormal probability distribution are estimated using mean and standard deviation statistics of lognormally transformed blowcounts. We calculate the statistics of random samples of varying size to estimate the population distribution of specific geologic units. Finally, we use geostatistics to describe the susceptibility in terms of spatial patterns and resolution.

Geostatistical Characterization of Susceptibility

Statistical and probabilistic methods can be used to characterize a unit. These characterizations assume that the unit is homogeneous; however, there is no estimate of the location or dispersion of this liquefiable portion of the deposit. We can use geostatistical methods to add a spatial component to the characterization. One of the distinguishing aspects of geologic datasets from other datasets is that the data belong to some location in space (Isaaks and Srivastava, 1989). Spatial data are likely to have characteristic distances or lengths at which they are correlated with itself, a property known as self-correlation or *autocorrelation*. Geostatistical methods provide an analytical approach to explore spatial autocorrelation and provide a more objective basis for deciding whether or not an observed spatial pattern is significantly different from random (O'Sullivan and Unwin, 2003). We will use the semivariogram to estimate the spatial correlation within the unit and kriging to provide an estimate of clustering.

Spatial autocorrelation of the susceptible units can be explored using *experimental semivariograms*. The experimental semivariogram describes the spatial structure of the values at the sample locations, that is, the degree to which nearby locations have similar values, or do not (O'Sullivan and Unwin, 2003). The semivariogram is a plot of the variance (one-half the mean squared difference) of paired sample measurements as a function of lag distance between the data points. The *range* value is the distance at which the semivariogram plateaus and corresponds to the distance over which sample points exhibit spatial autocorrelation. The plateau that the variogram reaches at the range is called the *sill* value. The *nugget* value is the y-intercept of the semivariogram and provides a measure of the short-scale variability of the data set. Short-scale variability is often associated with sampling or measurement error and/or the inherent natural variability of the attribute. In an "ideal" situation, the nugget is zero, since multiple values measured at the same location are expected to be equal. However, with most natural datasets this is rarely the case.

Once the spatial structure of the data is described using the model fit to the semivariogram, we can use the information to estimate a continuous interpolated surface. This interpolated surface will help us decide if specific regions within a given unit are more susceptible than others. Kriging can be used to determine if the unit should be subdivided to better represent liquefaction susceptibility. To predict values at unsampled locations, kriging methods use the semivariogram model to assign weights to the neighboring sample values. Kriging is often referred to as a "Best Linear Unbiased Estimator" (BLUE). It is "linear" because its estimates are weighted linear combinations of the available data; it is "unbiased" since it tries to have the mean residual equal to zero; and it is "best" because it aims at minimizing the variance of the errors (Isaaks and Srivastava, 1989).

To estimate a value at an unsampled location, a weighted sum of the surrounding measured values is used according to the following equation:

$$\hat{z}_s = w_1 z_1 + w_2 z_2 + \ldots + w_n z_n = \sum_{i=1}^{n} w_i z_i$$

where w_1 to w_n are a set of weights applied to sample values, z_1 to z_n, in order to arrive at the estimated value, $\hat{z}_s$ (Isaaks and Srivastava, 1989). The weights are assigned to surrounding values using the semivariogram model and the corresponding distance from the measured value to the prediction location.

4.0 SURFICIAL GEOLOGIC MAPPING

4.1 Quaternary geology

The surficial geology of the Boston area is dominated by deposits resulting from the extensive and repeated glaciation of the area throughout the Pleistocene (Woodhouse et al., 1991). The area was subjected to several episodes of glaciation. Glacial withdrawal during the late Pleistocene deposited large regions of glacial outwash and till throughout the area. Meanwhile, coastal processes influenced by the competing effects of crustal isostasy 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 deposited a sequence of fluvial sands and overbank silt deposits which line the margins of the river channel and are now present in the subsurface under the artificial fill units along the banks.

The surficial geology maps of the study area (Figure 2, Plates 1-8) developed for this project shows the areal distribution and composition of young, unconsolidated sediments. The map was based largely on previously published surficial geology maps, including Kaye (1976, 1978), Barosh et al. (1989), and Woodhouse et al. (1991). The geology map divides the surficial deposits into six units representing both the characteristics and the origin of the deposits. Mapped units include glacial drumlins (till), glacial ground and end moraines (till), glacio-fluvial deposits (glacial outwash plains, eskers, kames and kame fields), marsh deposits, beach deposits, and historic artificial fill. Regions of bedrock exposure and thin, discontinuous soil cover are also mapped. The most extensive units are the glacial outwash and the glacial till, which together comprise about 75% of the surface.

Glacial till is mapped as two separate units – glacial drumlins and ground moraines. 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 occur as round to elliptical hills and highlands reaching several tens to hundreds of meters above the surrounding terrain. Drumlins are often cored by local bedrock highs. Prominent drumlins include several in the Somerville/Medford area 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, with bedrock exposures occurring in zones of zero ground moraine thickness.

The till in both the drumlins and the ground moraine generally lies directly on the bedrock surface, and was deposited underneath the advancing glaciers and in places during the melting of stagnant or receding ice (Chute, 1966). 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 is generally well-consolidated and very dense. Large cobbles and boulders up to 1 meter in diameter occur rarely throughout the unit, but are often confined to the upper 3-4 meters (Woodhouse et al., 1991). Silty laminations and well developed internal structure is 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 grey. SPT blow counts in the till are variable but generally range from about 20 to refusal.

The glacio-fluvial deposits encompass a variety of deposits formed by the transport of glacially derived materials either from the edge of the glacier front or by subglacial flow, such as outwash, eskers, kettles, kame fields, and terraces. These deposits are grouped together for mapping, and are referred to as glacial outwash. The outwash deposits are composed primarily of stratified sands and gravels that are heterogeneous in three dimensions and vary in both density and consolidation. The thickness of the outwash deposits can reach several meters. The outwash deposits often overlie ground moraine till, and in several locations (e.g. Mystic Lakes-Fresh

Pond area) fill buried bedrock valleys up to about 70 m deep. The outwash units range in color from tan to brown and yellow, and tend to be loose to dense, with SPT blow counts from 5 to refusal.

Marsh deposits are common in the study area and occur both as salt marshes and estuaries along the coastal areas and as fresh water 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. Urbanization and suburban sprawl has resulted in a large amount of filling of these regions over the last 75 years.

Beach deposits represent the sediments deposited by ongoing modern coastal processes. In general these are composed of sand and gravel, with thicknesses ranging up to several meters. In some cases, extremely high blow counts in borings within the beach deposits indicate the presence of either buried boulders or fill that was subsequently buried by placement of sand during beach reclamation or stabilization.

We also recognized several stratigraphic units that occur in the subsurface but do not crop out at 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 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). Other subsurface units that we encountered in the borings, particularly in the regions of the detailed case studies, are described below in section 5.2.

4.2 Artificial Fill

A large portion of the downtown Boston area, including the waterfront areas, Back Bay, and Cambridge riverfront areas, are underlain by non-engineered artificial fill placed primarily during the mid 1800s to early 1900s (Figure 3). Properties of the fill layer are extremely variable. 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, rubble, trash, or other foreign materials (Woodhouse, et al., 1991). These areas were originally low-lying tidal marshes, estuaries, and floodplains adjacent to the Boston Harbor and the Charles River. Although tidal marsh, estuary, and floodplain deposits on the surficial geology map directly underlie them, these regions are mapped as artificial fill.

Detailed descriptions of the placement and extent of the fill units that are investigated in the detailed case studies (Section 5.2 and 5.3) are included below. If saturated and cohesionless, historic (non-engineered) fill is generally considered susceptible to liquefaction because it is loosely placed. The historic placement of fill described below represents the initial fill placement; however, over time fill is often excavated and replaced for engineering purposes. Most of the fill underlying newer buildings in Boston is engineered fill rather than the loosely placed historic fill discussed here. The historic fill likely remains beneath historic buildings and

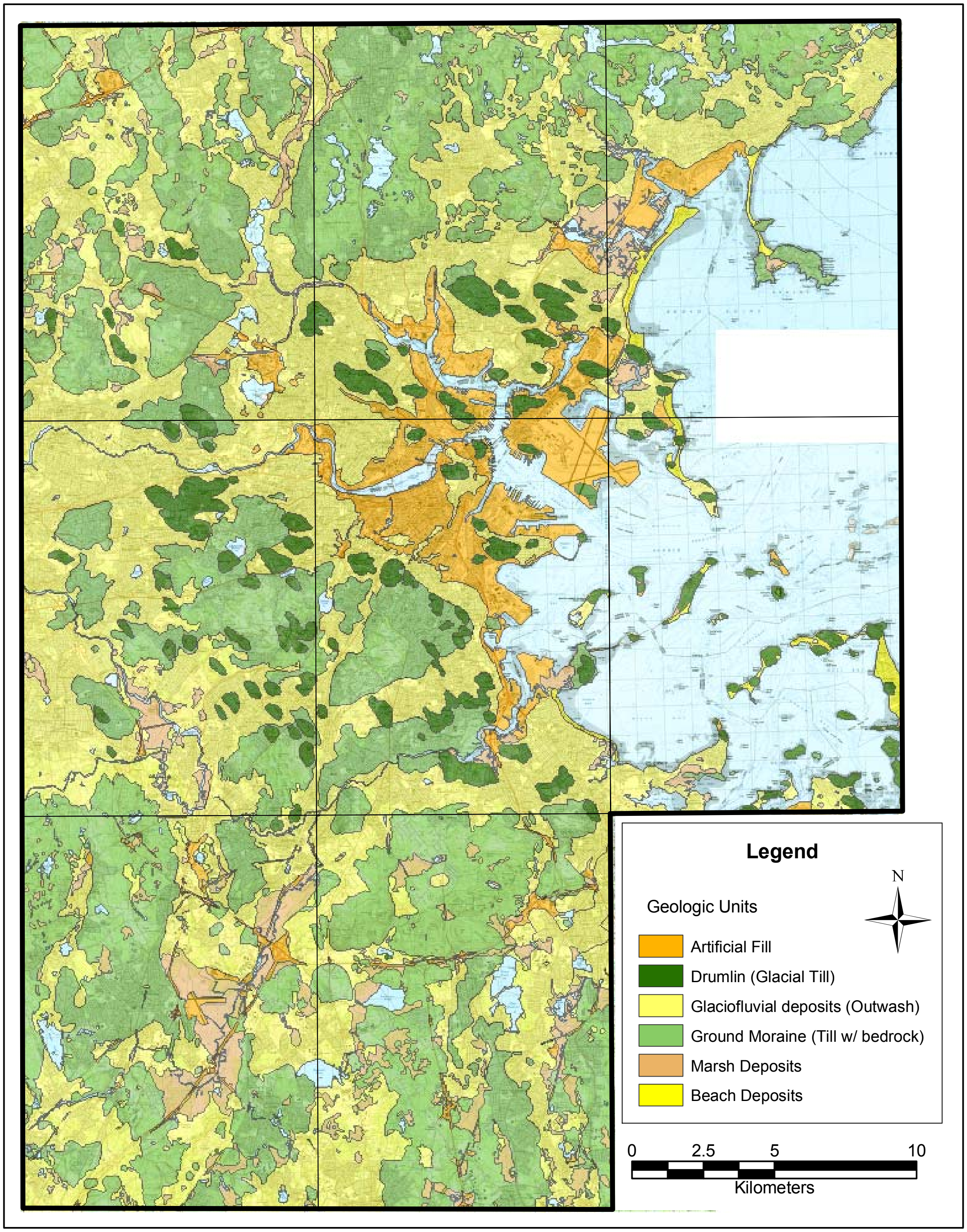


Figure 2. Regional surficial geology map of the Boston area. See Plates 1-8 for individual quadrangle maps.

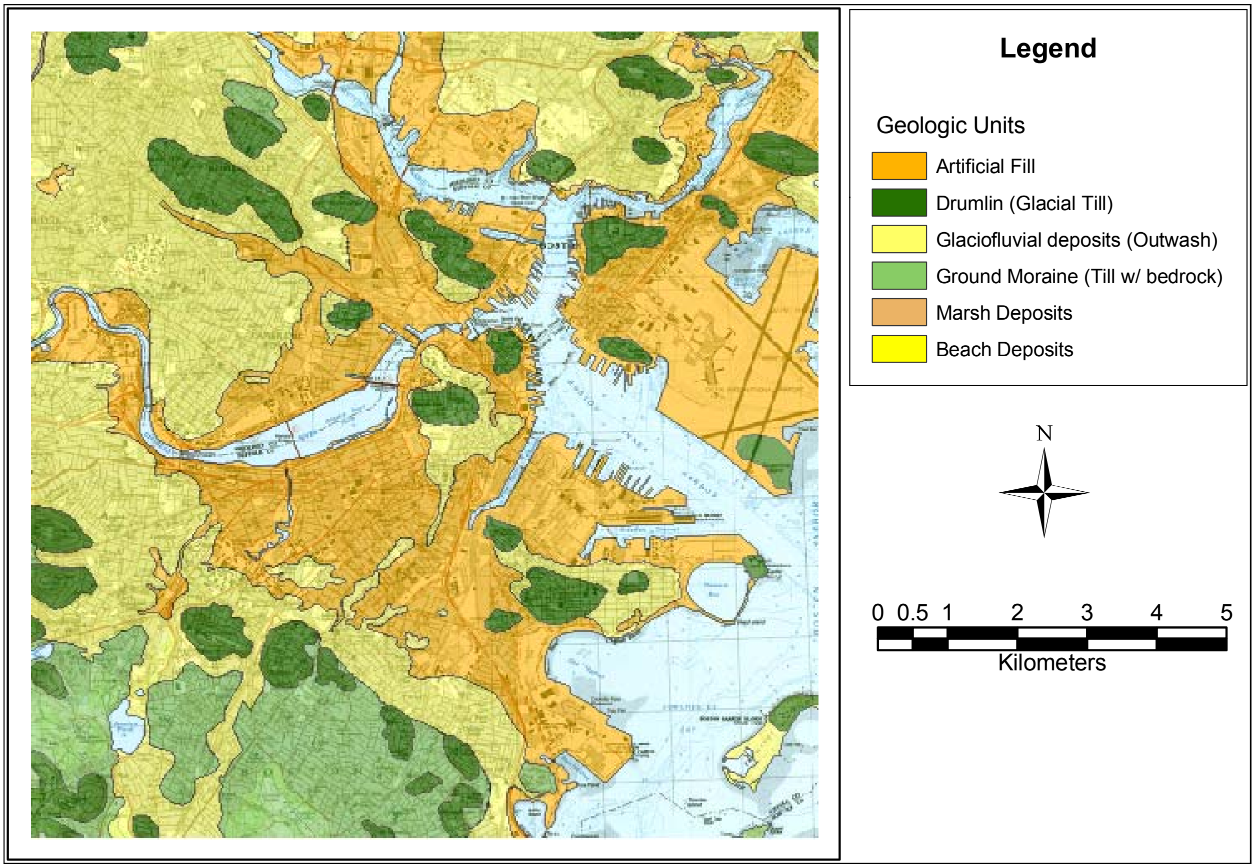


Figure 3. - Detailed map of surficial geology and fill in downtown Boston

roadways. Engineered fill if properly placed and compacted is usually dense and not susceptible to liquefaction.

Cambridge Fill

The present day shoreline of Boston and Cambridge along the Charles River is considerably different than the original historic coastline. The artificial fill in Cambridge was placed over former tidal marshlands upon completion of a granite seawall in 1890 (Woodhouse, 1991). The artificial fill unit in the Charles River Basin is underlain by Holocene fluvial, coastal beach and estuarine sediments consisting largely of sand and silty sand. The depositional environment of these units and the relatively shallow groundwater table causes them to be potentially prone to liquefaction.

The artificial fill unit on the Cambridge side of the Charles River ranges from 0 to 26 ft in thickness across the study region with a typical thickness of 10 to 15 ft. The bottom portion of the fill unit was obtained from the Charles River Basin and consists of silt, sand, and clay sized particles. The fill was dredged from the river and pumped into the area between 1890 and 1899

(Horn and Lambe, 1964). Layers of miscellaneous fill consisting of sand, silt, and clay-sized particles as well as building debris and trash were placed on top of the hydraulic fill at various times thereafter. Underlying the fill layer are former tidal marsh deposits, outwash and marine sand deposits, followed by a thick deposit of marine clay known as Boston Blue Clay. Glacial till and bedrock underlie the clay deposit. The geologic units of interest for liquefaction include deposits which are granular and saturated. Deposits meeting these criteria underlying the study area include: artificial fill, alluvial and estuarine deposits, and the marine sand and outwash deposits. Although the estuarine deposit primarily consists of organic peat and silt, in some areas, varying amounts of granular material are present as a result of deposition from stream and river channels running through the marsh deposits.

Boston Fill

As shown in Figure 5, the area surrounding the original Shawmut peninsula was filled gradually over a century or so. Each filling event used specific source material and a different filling method; therefore, it is useful to break up the fill units into subunits. Each subunit can then be characterized. Figure 6 presents the twelve fill units used in this study: Charlestown and Cambridge, Back Bay, West Cove, Mill Pond, East Cove, South Cove, South Bay, South Boston, Marine Park, Columbus Park, and East Boston. The fill history for each unit is described below.

Figure 4. Boston Fill Regions and Location of CA/T Soil Borings

The filling of the Back Bay also included the area now referred to as South End. This area, almost 600 acres, was filled over a period of 150 years and as a result of numerous projects. The source material varies from gravel extracted from nearby hills or brought in by railroads from as far away as Needham to household ash and cinders to mud from the basin itself. Most of the source material brought in by rail was sand and gravel from kame terraces or eskers. For the most part, filling was accomplished by dumping material from carts or railcars at the shoreline.

The majority of filling followed the construction of the Mill Dam and subsequent railroad embankments that crossed the Back Bay (Seasholes, 2004).

Fill was placed in the East Cove region over 300 years. The majority of East Cove was filled by individual entrepreneurs with any material that was inexpensive and readily available. This material was generally loose, although not always cohesionless. Most often the fill was trash collected from nearby homes and businesses. In addition to trash, East Cove was filled with sunken ships, trees, animal remains, gravel, and clay. The remains of the wood piles that supported the early sea walls and wharf buildings were also left in place when the area between wharves was filled. (Seasholes, 2003).

South Boston is composed of 1,013 acres of filled land and only 579 acres of original land. The filling of South Boston began in 1805 and continued into the late 20th century. Early filling was mainly marginal and concentrated in the southwest corner of South Boston. The majority of the fill that was placed in the late 19th century and in the early 20th century was placed by hydraulic dredge and consists of fine, silty sand with some clay. (Seasholes, 2003.)

Like most of Boston's coves, South Cove was filled with a broad array of materials including clay, gravel, coal ash, trash, and dredged mud. Many of the early wharves in the region were constructed on wood pile foundations. As the land between the wharves was filled, the wharves and the pile foundations became part of the mainland. The majority of South Cove was, however, filled in two main efforts by the railroads. Much of the soil used for these filling operations was granular in nature. Since the fill areas were broad, the fill was often placed in layers.

Much like South Cove and East Cove, West Cove was filled with a broad range of materials over a span of nearly 100 years. The majority of the fill material consists of granite blocks, gravel, and debris. The data that we have in West Cove are concentrated in one area. This area was one of the first and last areas filled. Consequently the fill in this area is highly heterogeneous.

Boston's South Bay was filled over a period of nearly 200 years. Early filling consisted mostly of the construction of shallow water wharves. The wharves were typically built on timber cribbing or wood pile foundations. Stone, gravel, and trash were used to fill the wharves. In the 1830s fill was taken out of the South Bay flats to fill the South Cove. From 1840 to nearly 1900, fill was placed back in the areas that had been excavated. The majority of this fill consisted of gravel imported from nearby Hope Farm. (Seasholes, 2003) Over the next 50 years, the railroads filled land to build new tracks and station houses. The majority of the fill materials placed at this time consisted of ash, debris, and gravel from Fort Hill (Seasholes, 2003.) In 1956, the state and the city began construction of the Southeast Expressway across South Bay. The expressway was built on fill piled behind an earth embankment. The construction of the Southeast Expressway pushed up the bottom mud in the rest of the Bay. This mud consisted mostly of "sewage, decaying organic matter, and fuel oil" and was reported to emanate a stench that could be smelled up to one mile away (Seasholes, 2003.) A commission concluded that the bay was nothing but an "open cesspool" and recommended filling the bay completely. In 1964, a culvert was built to carry the Roxbury canal to the Fort Point Channel and the remainder of the South Bay was filled. (Seasholes, 2003)

Like all filled areas of Boston, Logan Airport was filled in multiple phases using many different materials. Logan Airport opened in 1922. The original 122 acres were constructed on the Bird Island Flats, a set of small islands separated by tidal embayments (Haley & Aldrich, 1991.) Early fill placed in the flats consisted of organic mud and sand and was placed by dredge. Later fill consisted of blast-rock debris and sandy gravel. Since little of this material was compacted during placement, we anticipate that the fill material is loose.

The earliest filling of Mill Pond began in the 1640s when a dam was built across the pond to support four grist mills. The dam was constructed out of wood cribbing and gravel. Mass filling of Mill Pond began in 1807. Cartloads of gravel were hauled from Copp's Hill and dumped in the pond. From 1809 to 1810 a great deal of fill was imported from Beacon Hill. The continued growth of the railroads throughout the 19th century fueled the filling of Mill Pond. By 1900, the original pond was almost entirely filled. Archaeological explorations were completed in the late 1980s for the Central Artery project. These excavations revealed many layers of fill in Mill Pond. Some layers had high concentrations of artifacts including broken dishes and bottles. Some layers had no artifacts. Recent excavations have also revealed "huge blocks of granite, pieces of steel, whole walls, debris and dirt, and every conceivable kind of building material" in the more recently placed fill (Seasholes, 2003).

The southwest shore of Charlestown was filled over nearly 100 years. The area was first filled in 1804 to make new land for the state prison. The majority of the area was filled during the late 1870s and early 1880s with gravel that was cut from Bunker Hill. This material is generally cohesionless and loose. Small areas in the vicinity of the original Prison Point and at the north end of the southwest shore were filled with unknown materials. Early wharves along the waterfront were most likely filled with whatever material was available and easy to obtain. The fill along the original shoreline most likely partially consists of timbers and granite blocks that were part of the original wharves and that were left in place during later filling efforts.

5.0 SUBSURFACE CHARACTERIZATION

5.1 Geotechnical Borehole Database

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, SPT N-values, and x-y coordinate values. The soil samples are characterized by a brief soil type (i.e. sand, silt, silty sand, clay, etc.) and a detailed sample description. When available on the original boring log, stratigraphic unit is also associated with individual soil samples. The stratigraphy is characterized by geologic unit and depth to top and bottom of each unit. If the original soil boring log did not have stratigraphy specified, the stratigraphy field was left blank. In some cases specifically for data associated with the Boston and Cambridge case studies, the stratigraphic unit was modified slightly from the original boring log in order to conform to a more uniform naming convention. In the Cambridge case study (I), the stratigraphic units are artificial fill, organic deposits, upper sands (alluvial or estuarine sands), marine sand, marine clay, glacial till, and bedrock. In the Boston case study (II), the stratigraphic nomenclature is more diverse.

In addition to the stratigraphic and sample descriptions, information regarding the general project information and test boring information were entered into the database. The four primary data entry tables are illustrated in Figure 5. The boxes beneath each entry table shown on Figure 5 list the information included in each table. The Sample Description Lookup table was not a data entry table. It stored assumed values for unit weights and fines contents for the liquefaction calculations. The unit weights and fines contents were linked with the soil type (sand, silty sand, etc.). Within each test boring there are several stratigraphic units and one or more soil samples. The soil samples and stratigraphy are linked to the appropriate location by the unique field: Boring _ID.

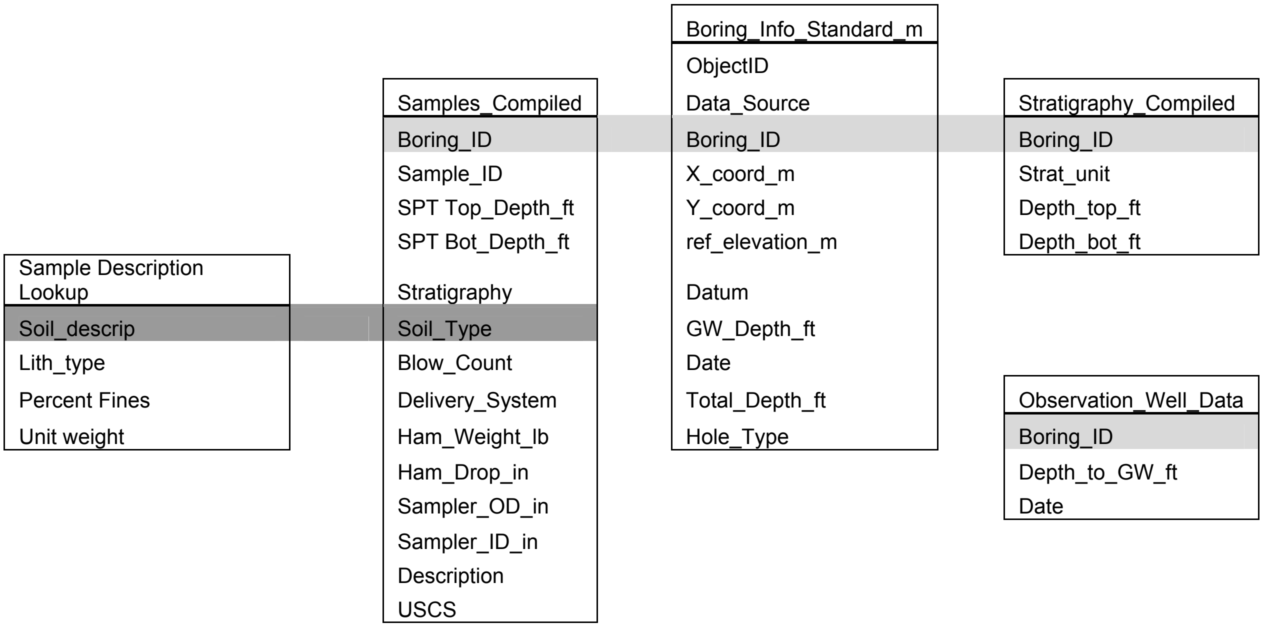


Figure 5. Digital boring database structure

The database structure easily allowed for importing and exporting data to and from other programs for analysis. Queries were created within the database to segregate and calculate required information such as all samples in the artificial fill or the thickness of a particular geologic unit. The liquefaction analysis was performed within a query in the database and is stored in a separate table. The liquefaction calculations followed the state-of-the-science as described by Youd et al (2001). For the investigation of spatial structure, the information was imported into a Geographic Information System (GIS; ArcGIS 8.2) for geostatistical analysis and mapping through a “dynamic” link with the database.

Data for this project were acquired from many sources. An electronic collection of data (1905 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. Sample information was not altered. In addition, electronic images of 12,782 boring logs and their location coordinates were acquired from the MWRA. Of these, data from 119 boring logs were hand-entered into the database. Additional MWRA logs were examined for the surficial geologic mapping and for a qualitative assessment of liquefaction susceptibility. The Boston Society of Civil Engineers (BSCE) 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 study, 715 borings were collected in and near the Cambridge fill unit along the shore of the Charles River. Permission was sought from the owners of these properties and the participating geotechnical consultants. The resulting geotechnical database from all of the aforementioned sources includes 2963 borings. The boring locations from the complied database as well as MWRA database are shown on Figure 6.

5.2 Case Study I – Cambridge Riverfront Area

Our first case study is in the nonengineered artificial fill unit in Cambridge along the Charles River as shown in Figure 7. As discussed above and shown in Figure 3 and Figure 4, the surficial geology of this area is artificial fill. Figure 7 shows the colonial shoreline for this area along with the current shoreline. The fill was placed over estuarine and marsh deposits overlying marine sand and clay. Based on surficial geology alone and the classification presented above, this unit is highly susceptible to liquefaction. Case Study I examines how geotechnical borings can be used to improve regional liquefaction mapping criteria using statistical methods.

Statistical Characterization

While mapping the surficial geology is a helpful and important first step in identifying potentially liquefiable units, additional quantitative analysis of the soil properties is possible when test boring data are available. Because the goal is to produce regional hazard maps rather than site-specific liquefaction analyses, a balance must be met between the regional scale of geologic units and the local site-specific scale of test boring data. A surficial geology-based characterization of hazard will usually result in a single estimate of susceptibility over the entire geologic unit. Many previous studies have used geotechnical boring data in liquefaction maps as a supplement to geologic mapping. The boring data are used to construct detailed cross-sections, characterize the geologic unit, and to spot-check the liquefaction susceptibility based on SPT blowcounts. In many geologic environments (especially nonengineered artificial fill), data from boring logs are highly variable. Therefore, as more boring data are collected, the less clear the classification is. Most previous studies have stuck with a single deterministic measure of liquefaction susceptibility that does not incorporate the variability of geotechnical boring data. Valuable information acquired from the test boring data is lost in a simplified classification. We therefore set out to develop mapping criteria that explicitly categorize the variability of liquefaction susceptibility over a geologic unit.

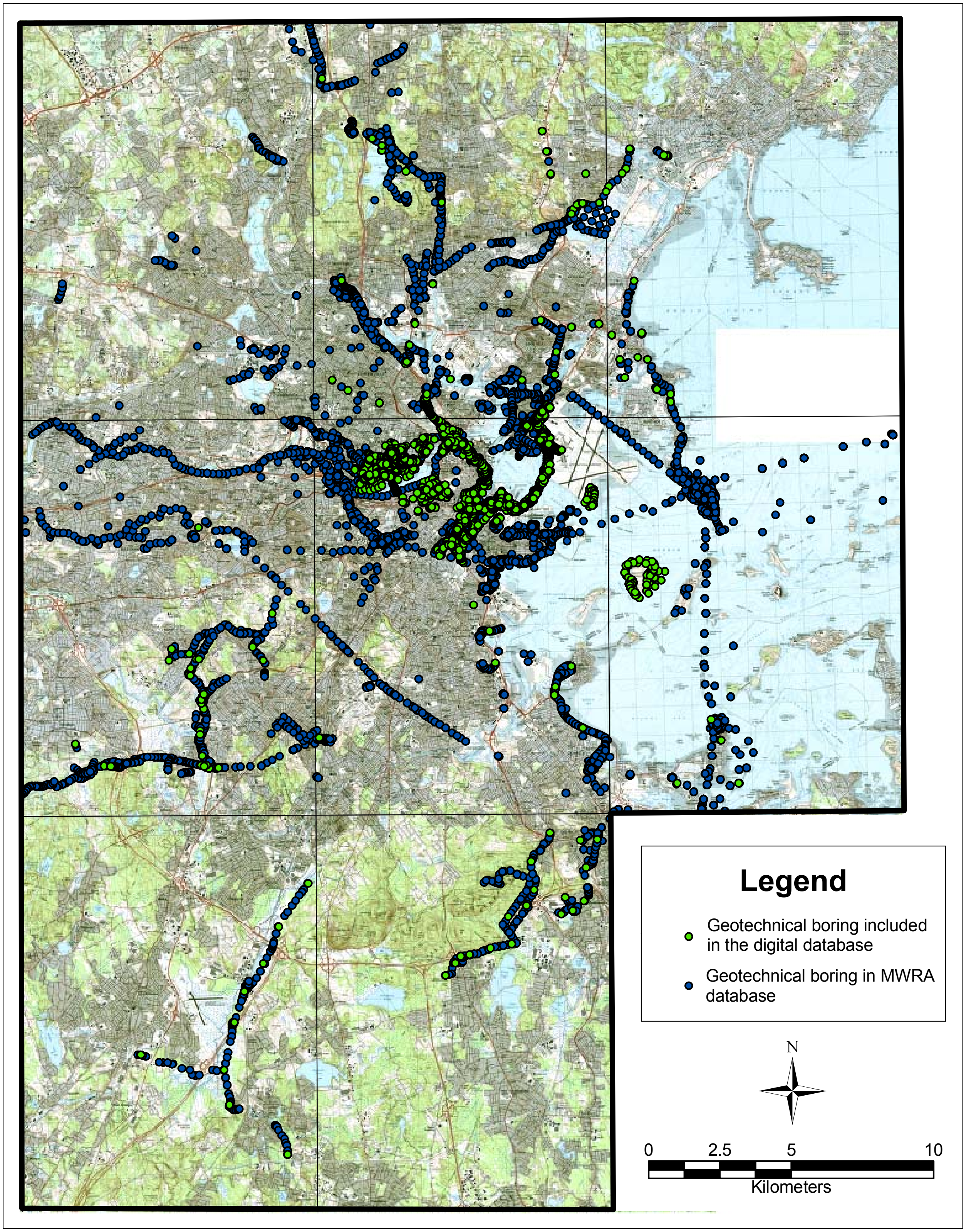


Figure 6. Location of geotechnical borings used in this project, include borings compiled into our digital database and borings from MWRA used to check geologic mapping.

To further classify geologic units with respect to liquefaction and with the goal of providing a new mapping criteria based on a statistical distribution of liquefaction susceptibility, we explored the statistics of the boring data – blow counts and liquefaction susceptibility in terms of trigger accelerations and susceptibility categories. All samples with a depth of less than 50 ft were queried from the database and analyzed for liquefaction susceptibility. These data include cohesionless as well as cohesive samples and therefore form a complete sample of the soils in the area. Initially we include the cohesive samples in our sampling in order to determine the overall extent of liquefiable material (versus nonliquefiable material). Eventually, we investigate susceptibility by geologic unit which provides a first pass filter on susceptible material (i.e. marine clay is not susceptible, marine sand is susceptible).

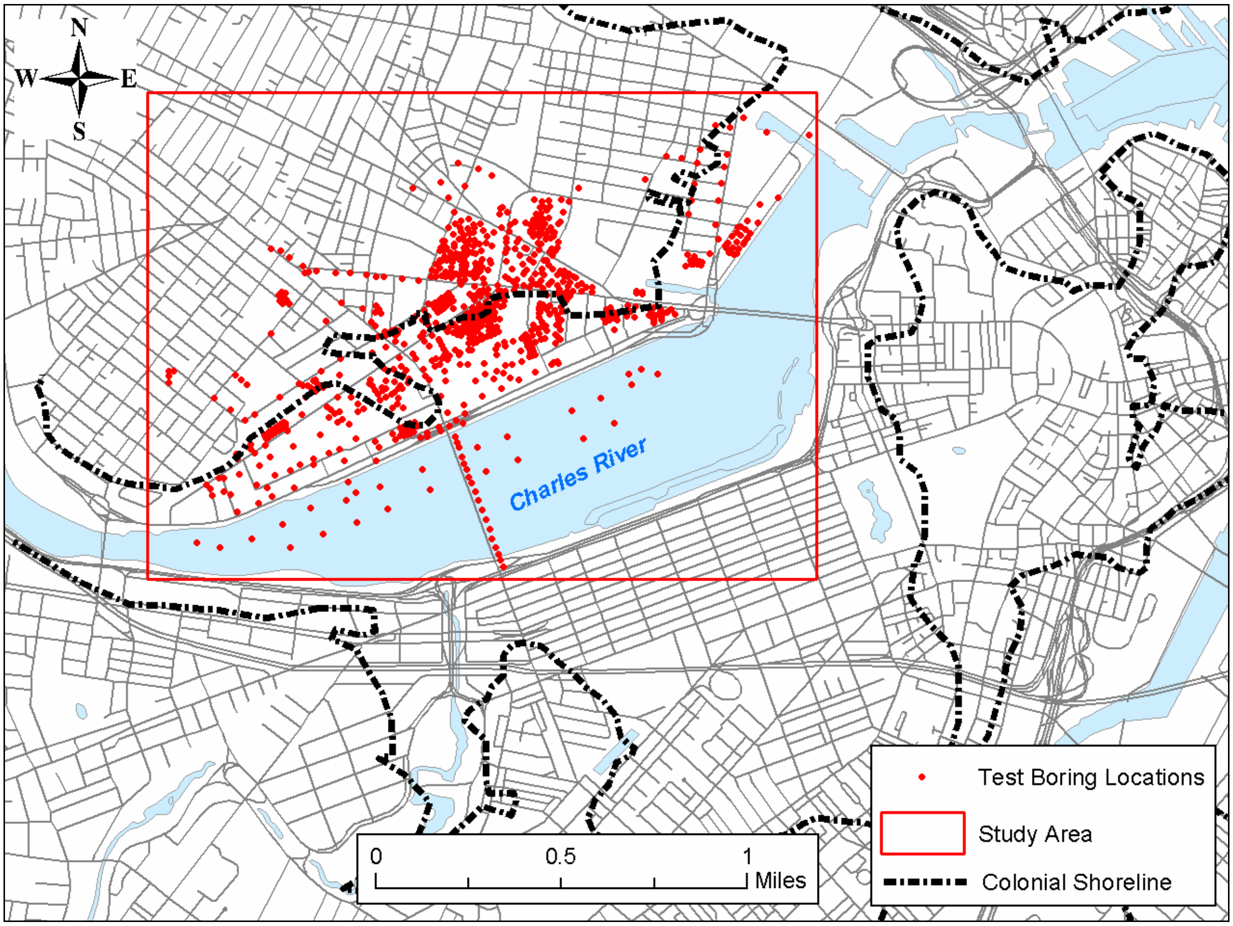
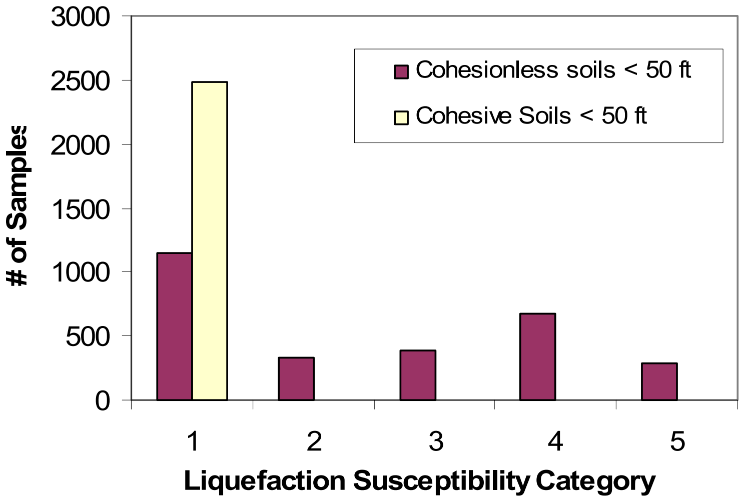


Figure 7. Case study area I: Cambridge riverfront area. The colonial shoreline is shown.

We use deterministic category values to investigate the distribution of liquefiable materials. Again, the category values refer to the trigger acceleration that would lead to liquefaction of the soil. The category values refer to the liquefaction susceptibility of the soil sample, rather than the geologic unit. A category 1 indicates that the soil sample will not be expected to liquefy and a category 5 indicates that the soil sample will liquefy with a peak ground acceleration less than 0.1 g. The distribution of the sample category levels provides an estimate of the distribution of liquefiable soils in the geologic unit. A histogram presenting the category values for all cohesionless and cohesive samples with depths less than 50 ft is shown in Figure 8. The cohesive samples all show up as category 1 values (>2000 samples). The majority of these samples are from the marine clay deep in the profile. The cohesionless samples are distributed across the five categories where the category 1 values are associated with unsaturated sands or sands with corrected blow counts greater than 30.



Liquefaction Susceptibility Category	Criteria
1	No liquefaction
2	$0.3g<PGA_{trigger}$
3	$0.2g<PGA_{trigger}<0.3g$
4	$0.1g<PGA_{trigger}<0.2g$
5	$PGA_{trigger}<0.1g$

Figure 8. Histograms of category values for samples in the Cambridge study area.

In order to investigate the liquefaction susceptibility of specific geologic units in the Cambridge area, samples from the artificial fill and underlying Holocene sand units were queried from the database. We prefer to investigate the liquefaction susceptibility by stratigraphic unit; however, one of the challenges in characterizing units over such a broad area and different projects is the difference in classification schemes used by various geologists. The borings cover a range of 6 square km, and 54 projects over 73 years. Therefore, it is difficult to find a consistent stratigraphic terminology to characterize the soils. This challenge is further exaggerated when we later try to characterize units over the entire Boston region. Over the Cambridge study area, alluvial, estuarine, and marine sands are all Holocene sands found beneath the fill. Sometimes one or two are broken out as distinct units in the same boring. Other times, the marine sand might encompass what another geologist would call alluvial sand. Therefore, we are forced to group soil units. Grouping by soil description and classifying statistically provides an additional means of classification.

We use the standard penetration test (SPT) blowcounts, available in most of the borings, to help classify the units, and therefore determine similar units. SPT blowcounts have been empirically linked to soil density, strength, and liquefaction susceptibility. The sample's SPT blow counts were corrected based on the correction factors provided in Youd et al. (2001). The corrected blow counts, $(N_1)_{60}$ values, were then separated based on their geologic description. The summary statistics and distribution of $(N_1)_{60}$ values for each geologic unit were explored. Results indicate different distributions and summary statistics between the fill layer, the

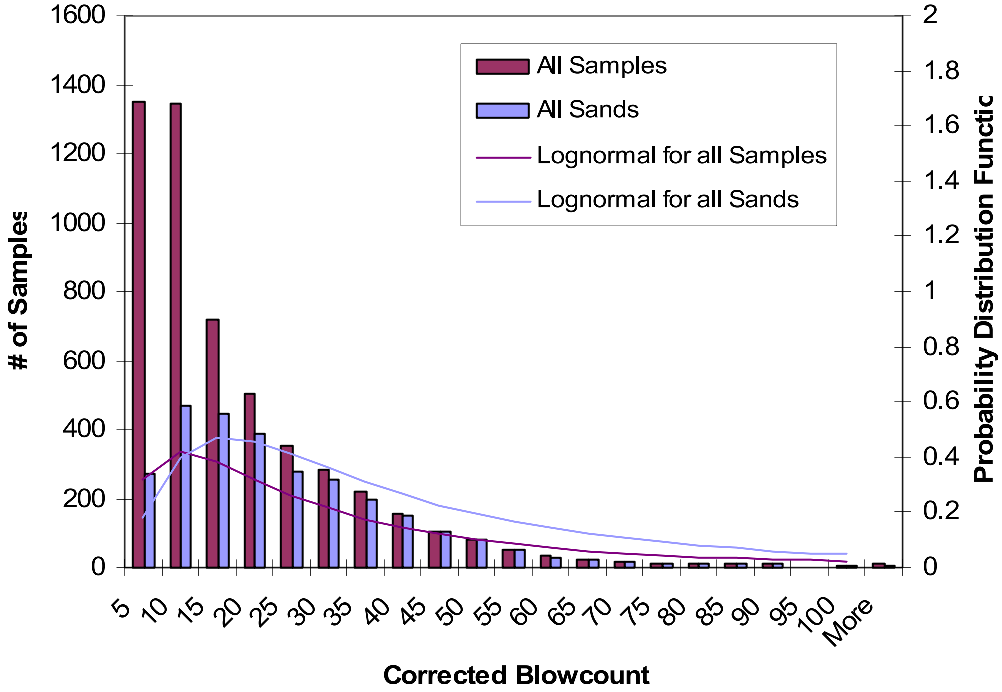


Figure 9. Histogram of corrected blow counts for all samples and for all sand samples (with sample depths less than 50 ft).

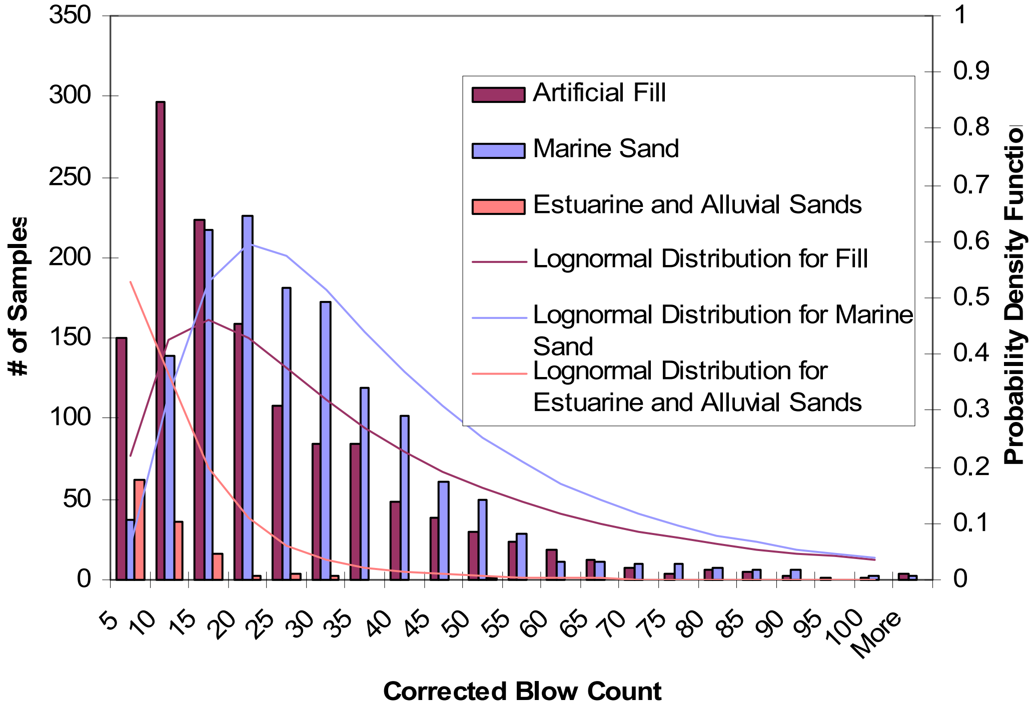


Figure 10. Histogram of corrected blow counts for the artificial fill, the alluvial and estuarine sands, and the marine sand.

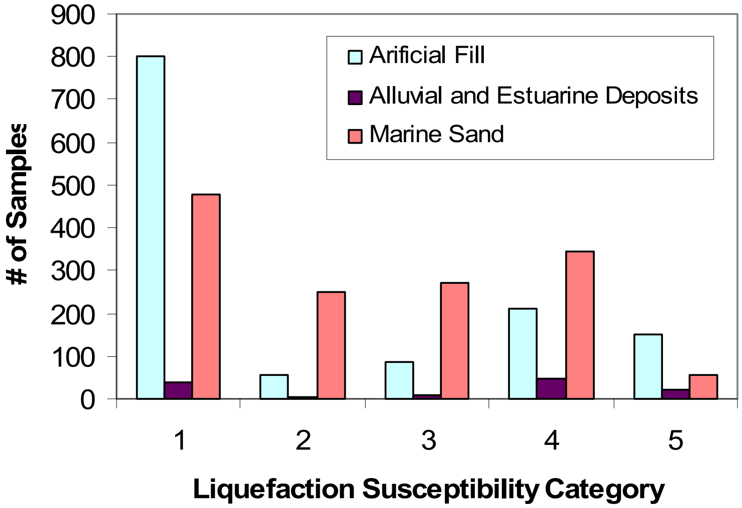
underlying estuarine and alluvial sand deposits, and the marine sand deposit. Figure 9 shows a histogram of corrected blowcounts for all cohesionless samples with depths of less than 50 feet. Histograms of corrected blow counts for artificial fill, marine sand, and alluvial and estuarine sands are shown in Figure 10. The estuarine and alluvial sands are not pervasive enough across the site to constitute regional mapping; however, where they exist, they are a loose deposit with an average corrected blow count of 7.0. The lognormal probability density function for each data set is also shown. The appropriate lognormal distribution is estimated from the mean and standard deviation of the lognormally transformed data. From the comparison of the histograms, a difference in corrected blow count distribution is apparent. All three distributions are approximately lognormally distributed but the marine sand is the most positively skewed. As shown, the artificial fill has a greater frequency of low blow counts than the marine sand. The alluvial and estuarine sands are not extensive but their distribution has the highest frequency of low blowcounts of the three stratigraphic units.

Descriptive statistics for each unit are summarized in Table 1 and confirm the visual results from the histograms. The artificial fill has a mean $(N_1)_{60}$ value of 20.1 and a median value of 14.6, while the mean and median value of the marine sand are 25.4 and 22.1, respectively. The alluvial and estuarine sands have a mean of 7.0 and a median of 4.9. While the measures of central tendency are different for the three units, the measures of spread, or variability, are relatively similar. The standard deviations of the marine sand and artificial fill are 16.3 and 17.0, respectively indicating that the units have similar widths to their distributions. The alluvial and estuarine sands have a lower standard deviation of 6.5. Another way to measure variability of the datasets is by calculating the *coefficient of variation*, c_v, which provides a relative measure of data dispersion compared to the mean: $c_v = \sigma/m$. When the c_v is small, the data scatter compared to the mean is small; when the c_v is large, the amount of variation is large. The c_v values for the three datasets are all relatively high, ranging from 64% to 92%, indicating a large variation of data values within each of the datasets. It is not surprising that the blow counts yield a high degree of variability considering the numerous sources of error involved in measuring and correcting the values as well as the possibility of several different units and local depositional variability over the area. The standard penetration test is highly variable; however, it is still the primary test used for field investigations of liquefaction susceptibility. Of course, not all of this variation results from error; it can also result from inherent spatial variability in the unit.

Statistic	All Sand	Artificial Fill	Marine Sand	Alluvial and Estuarine Sands
mean, m	22.1	20.1	25.4	7.0
median, M	17.7	14.6	22.1	4.9
Std Dev, σ	17.0	17.0	16.4	6.5
Coef. Of variation, c_v	0.77	0.85	0.64	0.92
Count, n	2823	1307	1399	124

Table 2. Summary statistics of $(N_1)_{60}$ values

In terms of interpreting blowcounts in terms of liquefaction susceptibility, two issues exist. First, low blowcounts in the estuarine and alluvial sands are often associated with silty sands or silts which may not be liquefiable. Also, low blowcounts in the fill may be associated with silty or clayey soils or unsaturated soils. Thus, the blowcounts are more easily characterized but may be misleading in terms of liquefaction susceptibility. To look at the distribution of liquefiable materials in the sands, histograms of category values in the artificial fill, the alluvial and estuarine sands, and marine sand are shown in Figure 11. The large number of category 1 values in the fill is associated with unsaturated samples in the upper portion of the fill. When comparing the distribution of category values in the artificial fill and marine sand, the marine sand is uniformly distributed across category 2, 3, and 4 but has a lower number of category 1 values. The artificial fill category values are shifted more towards 4 and 5 values (27% in category 4 or 5) but have a higher frequency of 1 values. The category values in the alluvial and estuarine sands are predominantly high values (57% in category 4 or 5). The category value distributions are no longer lognormally distributed; therefore, we will not attempt to fit a common probability distribution to the data.



Liquefaction Susceptibility Category	**Criteria**
1	No liquefaction
2	$0.3g<PGA_{trigger}$
3	$0.2g<PGA_{trigger}<0.3g$
4	$0.1g<PGA_{trigger}<0.2g$
5	$PGA_{trigger}<0.1g$

Figure 11. Histogram of category values in three stratigraphic units: artificial fill, alluvial and estuarine sands, and marine sand.

The preceding observations are consistent with our understanding of the depositional environments and how deposition affects density of subsurface conditions. The non-engineered fill, tidal alluvial and estuarine marsh deposits are expected to be relatively loose as a result of their placement or deposition. The marine sand is older, and more highly compacted, and therefore is expected to be denser. These results indicate that the susceptible layers (saturated and cohesionless materials) should be evaluated as three distinct units. Because we are interested in regional mapping within the 5 square km case-study area, we will focus on the artificial fill and the marine sand. The alluvial and estuarine sands are not pervasive enough across the study area for regional mapping.

Probabilistic Characterization of Susceptibility

In order to characterize liquefiable units regionally, we are faced with the dilemma of losing detail in order to provide a unique and concise description. An alternative to the deterministic or statistical descriptions discussed so far is to use a probabilistic description of the sample population. The deterministic description reduces the variability inherent to the deposit to a single estimate for liquefaction susceptibility: "Very high susceptibility: the fill unit will liquefy when the peak ground acceleration is less than 0.1 g." A probabilistic characterization will include all aspects of a population as a distribution of hazard values. The resulting probability distribution can be used to determine alternate descriptions of hazard: "10% of the fill unit will liquefy when the trigger value is 0.1 g." A probabilistic characterization relies on our sample estimates of the population characteristics; therefore, we need to understand the accuracy of these distribution estimates as related to the sample size. Because corrected blowcounts were lognormally distributed and category values did not demonstrate a common distribution, we will focus this section on the corrected blowcounts to characterize liquefaction susceptibility.

The statistical characterizations presented above include 715 borings. A collection of that many borings densely spaced is not realistic for many liquefaction mapping projects; therefore, one goal of this case study was to provide guidelines as to how many borings would be necessary to characterize a regional geologic unit. Our study is based on three geologic units present in the case study region: artificial fill, alluvial and estuarine sands, and marine sands. The Cambridge fill unit under investigation is approximately 6 square km. In general, artificial fill units in Boston are difficult to characterize as they may vary significantly across this large of an area; however, the Cambridge fill was placed over a relatively short period (approximately 10 years) and came from a relatively consistent source (the Charles River channel) as discussed in a previous section on fill history. Therefore, for an artificial unit, we expect it to be relatively consistent. The alluvial and estuarine sands and the marine sand, all natural deposits, should be more consistent resulting from a constant deposition environment and source. Although the alluvial and estuarine deposits are intermittent across the region, the consistent depositional environment should result in a consistent sample population.

By selecting a random sample of borings and then quantifying the results of all the data in the set of borings, we can evaluate the number of borings needed to characterize each unit probabilistically. We will assume that the entire sample of 715 borings is enough to provide an accurate estimate of the population; and therefore, we set out to determine what size random sample from the original sample is needed to match the population. The corrected blowcounts for all the random samples taken in the previous section are positively skewed and appear to be lognormally distributed; therefore, a lognormal transformation was performed for both the fill, the alluvial and estuarine sands, and the marine sand. By fitting a normal distribution to the transformed data using the sample mean and sample standard deviation as parameters, we can predict the cumulative probabilities for specific corrected blowcounts. All three distributions are fit by a lognormal distribution as shown in Figure 10 with the histograms.

Because we are concerned with which soil samples would liquefy, we designated a limiting blowcount. In the artificial fill, a sand soil sample at a depth of 15 ft with a blow count less than or equal to 8 would be expected to liquefy for the design earthquake (M=6.0, PGA=0.12 g). For the corrected blowcounts in the sample of 715 borings, the lognormal distribution predicts 25%

of the samples in the artificial fill are at or below the limiting blowcount. In the original sample, 25% of the samples are at or below the limiting blowcount. The limiting blowcount for the alluvial and estuarine sands is 7. The lognormal distribution predicts 65% of the samples in the alluvial and estuarine sands are at or below the limiting blowcount as compared to 63% of the samples in the original population. For the marine sand, the limiting blowcount is 6. The resulting lognormal distribution prediction is 3% of the samples are at or below the limiting blowcount whereas 5% of the actual samples met this criterion. Table 3 summarizes these results. The marine sand distribution is not perfectly matched by the lognormal distribution at these low blowcounts. Overall, the cumulative distributions match the sample populations as demonstrated by the similarity between percentage of samples and cumulative distribution percentages.

As stated earlier, the disadvantages of using corrected blowcounts to characterize a geologic unit for liquefaction is that you cannot account for grain size (silty soil samples) or saturation. In Table 3, the percentage of samples in each geologic unit that have trigger acceleration values less then 0.12 g (design earthquake) are listed. The trigger acceleration is a more definitive estimate of what samples are liquefiable for the design earthquake condition. For the artificial fill, only 15.5% of the samples are liquefiable as compared to 24.9% below the limiting blowcount. The difference in the alluvial and estuarine sands (33.9% instead of 62.9%) is also significant. In the artificial fill, this difference is attributed to unsaturated soil near the surface and silty soils in the fill. For the alluvial and estuarine sands, the difference predominantly results from the reduced susceptibility of silty soils. On the other hand, the marine sands are more liquefiable (7.4%) than estimated using the limiting blowcount.

The statistical estimates so far are based on the population of samples and estimate the volume of soil that is susceptible to liquefaction. Because the hazard maps will be two-dimensional, another way of looking at the susceptibility is by an estimate of area. Therefore, as an alternative, we estimated the percentage of borings that have at least one sample with a trigger level below 0.12 g. As shown in Table 3, the percentage of borings (which represents an estimate of area on the map) with at least one sample that is susceptible to liquefaction for the design scenario, is considerably higher than the volume estimate for all three geologic units. We also estimated that 40% of borings in the study would have at least one soil sample susceptible to liquefaction given the design scenario.

In order to determine the number of borings needed to accurately estimate the population distribution in both the artificial fill and the marine sand, six random samples of decreasing size were taken from the original population of 715 borings. Table 4 summarizes the cumulative lognormal distributions at or below the limiting corrected blowcount in the artificial fill and the marine sand for six sample sizes (200, 100, 50, 28, 14, and 7 borings). In the fill, the cumulative probability for $(N_1)_{60}<=8$ varies between 19.2% for 50 borings and 29.6% for 7 borings. If we take the original sample of 715 borings as the population (with 24.9% of the samples in the artificial fill below the limiting blowcount), all sample estimates are within 5% of predicting the true population percentage. In the marine sand, the cumulative probability for $(N_1)_{60}<=6$ was between 2.0% for 28 borings and 4.6% for 50 borings. All boring samples within the marine sand (with 4.9% of the soil samples in the artificial fill below the limiting blowcount) predict a cumulative distribution within 3% of the actual value. For the marine sand, the lognormal distribution underestimates the cumulative distribution below the limiting blow count for all samples. This is indicative of a poor fit in this region of the probability distribution.

	All units combined	Artificial Fill	Alluvial and Estuarine Sands	Marine Sands
Number of Samples		1307	124	1399
$\mu(\ln(N_1)_{60})$		2.66	1.66	3.04
$\sigma(\ln(N_1)_{60})$		0.86	0.75	0.67
Limiting Corrected Blowcount		8	7	6
% Samples below limiting blowcount		24.9%	62.9%	4.9%
% Samples with acceleration trigger value < 0.12 g		15.5%	33.9%	7.4%
ln(x<limiting blowcount)		25.1%	65.0%	3.2%
% Borings with acceleration trigger values < 0.12 g	40%	27%	46%	16%

Table 3. Comparison of sample percentages and lognormal distribution predictions

The percent of samples that are liquefiable based on the liquefaction calculations are also listed in Table 4. Again the sample percentages for the artificial fill are significantly lower than those found from the limiting blowcount approach. The predicted percent of liquefiable samples in the artificial fill using trigger acceleration values varies from 5.6% (50 borings) to 23.9% (28 borings). And the marine sand sample percentages are significantly higher than from the limiting blowcount approach. The predicted percent of liquefiable samples in the marine sand using trigger acceleration values varies from 0% (7 borings) to 14.3% (14 borings).

From a probabilistic standpoint, not all 715 borings are necessary to provide a reasonable estimate of the population. In terms of providing a probabilistic estimate of the corrected blowcounts, as few as seven borings provide a reasonable estimate of the lognormal distribution. The result is that about 25% of the samples show a corrected blowcount below the limiting value (8). Using the lognormal distribution, the sample estimates vary from 19.2% to 29.6%. If sample percentages were used instead of the lognormal distribution, the samples estimates vary from 20.2% to 37.0%. For the marine sand, only 5% of the population can be expected to have corrected blowcounts less than or equal to 5. The sample estimates using the lognormal distribution vary from 2.0% to 4.6% (all below the original population). Using sample percentages, the estimate varies from 0.0% to 14.3%.

		715 Borings	200 Borings	100 Borings	50 Borings	28 Borings	14 Borings	7 Borings
Artificial Fill	Number of Samples	1307	359	158	89	46	20	17
	% Samples <=8	24.9%	21.4%	29.7%	20.2%	37.0%	20.0%	23.5%
	% Samples amax <0.12g	15.5%	11.7%	13.9%	5.6%	23.9%	15.0%	23.5%
	$\mu(\ln(N_1)_{60})$	2.66	2.69	2.55	2.77	2.59	2.69	2.58
	$\sigma(\ln(N_1)_{60})$	0.86	0.86	0.85	0.79	0.92	0.82	0.94
	$(N_1)_{60}$ <=8	25.1%	23.8%	29.0%	19.2%	29.0%	22.7%	29.6%
Marine Sand	Number of Samples	1399	367	199	95	61	14	10
	% Samples <=6	4.9%	4.6%	8.0%	7.4%	3.3%	14.3%	0.0%
	% Samples amax <0.12g	7.4%	6.8%	8.0%	10.5%	3.3%	14.3%	0.0%
	$\mu(\ln(N_1)_{60})$	3.04	3.07	3.04	3.00	3.26	3.09	2.85
	$\sigma(\ln(N_1)_{60})$	0.67	0.70	0.73	0.71	0.71	0.73	0.57
	$(N_1)_{60}$ <=6	3.2%	3.2%	4.5%	4.6%	2.0%	3.7%	3.2%

Table 4. Comparison of Cumulative Lognormal Distribution for Corrected Blowcounts at or below the limiting value ($(N_1)_{60}$ <=8 for the artificial fill and $(N_1)_{60}$ <=6 for the marine sand) for different samples of borings.

This result shows the advantage of using a probabilistic characterization of a population to reduce estimate error. However, we still have the important problem that blowcounts are not a sufficient characteristic for determining liquefaction susceptibility (i.e. saturation and grain size are also needed). If we use sample percentages for liquefaction susceptibility (using acceleration trigger values), the estimate error is even higher. The sample estimates for liquefaction susceptibility in the artificial fill range from 5.6% (50 borings) to 23.9% (28 borings) when the population value is 15.5%. For the marine sand the sample estimates range from 0% to 14.3% with a population value of 7.4%.

In terms of providing a characterization of these units with the least amount of data, five to ten borings will provide an estimate that is within five percentage points in the artificial fill and two percentage points in the marine sand if the lognormal distribution is used. A larger degree of sample error results if raw sample percentages are used to estimate the population distribution. Using sample percentages, the estimates are consistent for sample sizes of 715, 200, and 100 but the estimate error increases significantly when 50 borings or fewer are sampled.

When a limited number of borings are available, a probabilistic characterization of the blowcounts can provide a reasonable estimate of the distribution of sample density in the unit. This can in turn provide an estimate of liquefaction susceptibility or hazard. The estimate may be high (and biased) if a large percentage of silty samples or unsaturated samples are present; however, it will be more certain than raw sample percentages. A geologic interpretation of the layer to determine saturation and extent of cohesionless soils should accompany the limiting blowcount analysis. Liquefaction hazard mapping criteria should then be linked with an estimate of how much of the unit is liquefiable. Proposed mapping criteria are presented in Table 5. Rather than the category values 1 through 5 presented earlier and used to characterize individual soil sample hazard, the proposed hazard categories are for regional units when geotechnical boring data are available.

In order to use corrected blowcounts to directly characterize liquefaction susceptibility, a limiting blowcount is required. This may be an issue when the stratigraphy is not uniform and/or known over the region. In the Cambridge case study, distinct layers were identified and characterized separately. In the larger Boston region, the stratigraphy is less well known. When stratigraphy is unknown or nonuniform, sample percentages are an appropriate estimate of liquefaction susceptibility. However, direct sample percentages have a larger degree of uncertainty than the cumulative lognormal distribution predictions used here. When insufficient boring data is available, criteria based on surficial geology should be used.

Hazard Category	Predicted volume of liquefiable materials in percentage	Geologic Units (Case Study I)
High Hazard	>15%	Artificial Fill, Alluvial and Estuarine Deposits
Moderate Hazard	<15% and >5%	Marine Sands
Low Hazard	<5%	

Table 5. Proposed regional hazard mapping criteria based on cumulative probabilities of lognormally transformed corrected blowcounts or sample percentages.

The proposed regional hazard mapping criteria listed in Table 5 will be used in developing the liquefaction hazard maps for Boston. When lognormally transformed corrected blowcounts are used to characterize the soil, special care should be made to ascertain if soils are silty in nature and/or saturated. Silty soils will be less liquefiable than predicted using blowcounts alone. Since unsaturated soils are not liquefiable, an unsaturated soil unit should be assigned a low susceptibility rating. If sample percentages are used to estimate liquefaction susceptibility, large estimate errors are expected and therefore the hazard classification should rely more heavily on the expected susceptibility of the geologic unit.

Spatial Variability

The probabilistic characterization of liquefaction units presented above assumes a homogeneous geologic unit. In nature, geologic deposits often vary systematically in depth and space. We set out to examine the spatial variability in two modes to determine if susceptible deposits should be characterized spatially as well as probabilistically. First, we investigated a systematic variation in blowcounts with depth to determine if the deposits are layered. Second, we looked at spatial variability across the site (in map view) to locate distinct zones of liquefiable materials.

When the corrected N-values are plotted against sample number (depth) for eleven borings with more than four samples in the fill, a negative sloping trend exists for each of the borings as shown in Figure 12. Some trends are more extreme than others, and some borings have high points at mid-depth as well as at the surface. The mean value captures the midpoint of the trend but does not adequately characterize the unit. With a general decrease in N-values with depth, the fill unit is less dense at the base, and therefore, the liquefiable portion of the fill will most likely be located near the base. In terms of liquefaction susceptibility, not only is the upper portion of the fill more dense, but it is also unsaturated. Therefore, in the histogram of category values in the fill unit (Figure 11), the large number of category 1 values (nonliquefiable material) result from unsaturated fill.

Because the low blowcounts are clustered spatially in depth, the homogeneous assumption made in the probabilistic characterization of the deposit is therefore not strictly appropriate. Although the probability distribution does not account for the clustering of low blowcounts at depth and high blowcounts near the surface, the knowledge of spatial clustering can be paired with the results of the probability distribution. The resulting inference would be that the liquefiable samples in the fill (samples with low blowcounts) are likely clustered at depth and therefore will likely lead to continuous volumes of liquefiable materials.

For the marine sand, the corrected blowcounts are plotted against sample number for all borings with greater than four samples in Figure 13. The marine sand does not have a consistent trend (as expected). For the 12 borings shown, there are two groups. One group of borings (5 out of 12) has very high values, especially near the top of the layer and the corrected blowcounts remain relatively high throughout the boring (generally above 30). The second group of borings (7 out of 12) has lower values (generally below 30), which tend to be more consistent throughout the boring. Therefore, the assumption that the marine sand is a homogeneous deposit is appropriate.

Horizontal Spatial Correlation

We have observed a systematic trend with depth in the blowcounts for the artificial fill indicating that the fill is essentially a layered deposit, with respect to density. The marine sand, on the other hand, is more uniform with depth. We would also like to consider spatial variability across the deposit – in the horizontal direction. Rather than identifying a Cambridge fill unit with a high hazard based both on surficial geology and the distribution of blowcounts, we can spatially identify zones of high, moderate, and low hazard within the fill unit. Geostatistical methods are used to assess the spatial correlation of liquefiable materials and to interpolate hazard across the region.

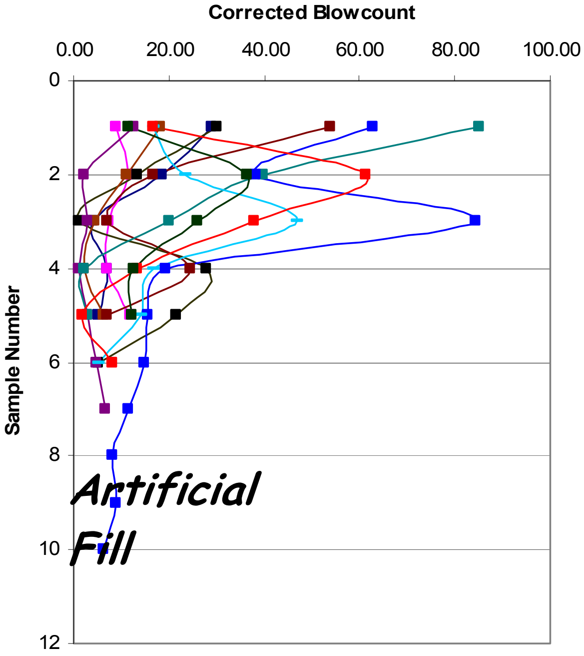


Figure 12. Corrected N-values plotted against sample number in the artificial fill for all borings with greater than four samples.

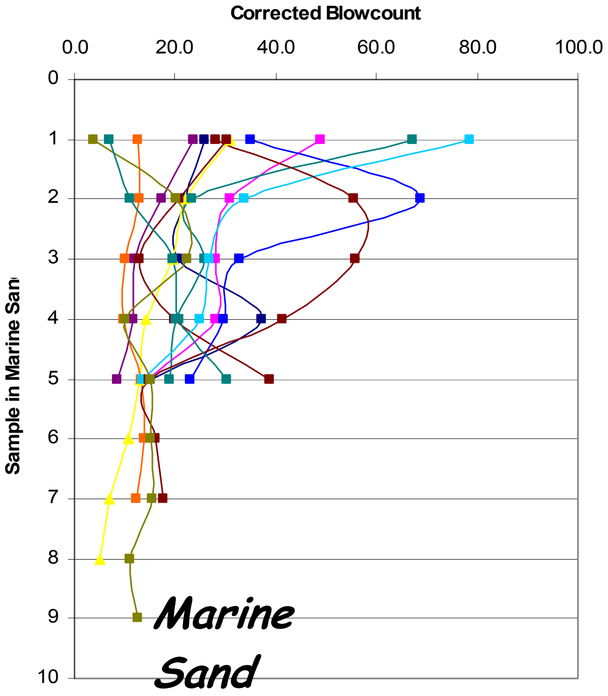


Figure 13. Corrected blowcounts plotted against sample for all borings with greater than four samples in the marine sand (sample one is first sample taken in the marine sand)

For the horizontal spatial correlation, each boring location can only supply one value. As a result, the systematic depth dependence of corrected blowcounts becomes very important. We can use a mean value, a minimum value (worst-case scenerio), or some weighted average (Liquefaction Potential Index). The Liquefaction Potential Index is theoretically very useful, but practically difficult to implement. Statistically, a mean value would be used as the best estimate of the value at that particular boring. However, we are trying to present liquefaction susceptibility, where the minimum value may be more relevant. Because N-values are taken over depth, the choice between minimum, mean, or maximum N-value depends on the assumptions we make in interpreting the geologic unit. If we assume that the geologic unit is homogeneous in all three directions, then the mean is the best estimate of the value at a boring. If, on the other hand, we believe that there is a systematic trend with depth which would result in low N-values spatially grouped either at the top of the deposit or at the base of the deposit, than either minimum values or an alternative criteria may be preferred. In the end, we care about identifying liquefiable units within the fill even if the mean-fill behavior is different; therefore, we will use the minimum corrected blowcount for each boring (or maximum category value) to characterize that location. This assumption is an approximate corollary to characterizing the loose portion of fill at the base of the unit. For the marine sand, although the mean value may be an appropriate estimate of the unit since the unit is fairly homogeneous with depth, a minimum value estimate will still have the benefit of identifying the least dense portion of the unit.

Figure 14 presents the semivariogram generated from the maximum susceptibility category for the fill unit associated with each location within the Cambridge portion of the study area. The *range* value for this dataset is approximately 200 m, indicating that beyond 200 m, there is no particular spatial structure in the data. For the semivariogram shown in Figure 6, the sill value is approximately 2.8. The nugget value for the semivariogram shown on Figure 6 is approximately 1.6, relatively high compared to the magnitude of the sill.

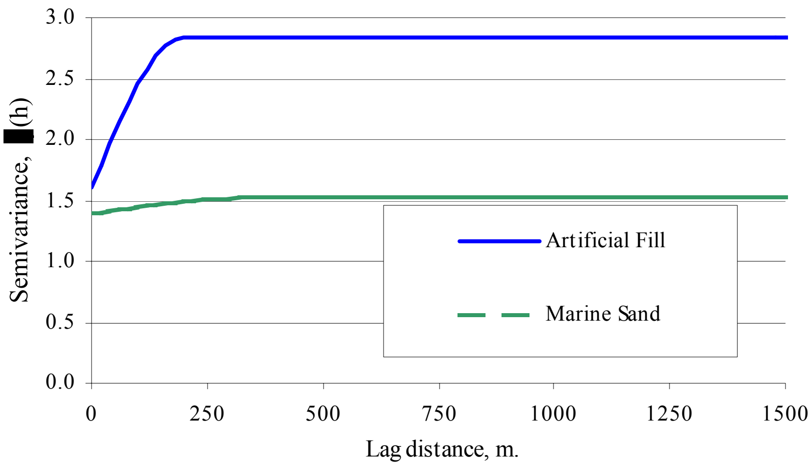


Figure 14. Experimental semivariograms for fill and marine sand

As compared to the fill unit, the spatial correlation of the marine sand is far less. As shown in Figure 14, the semivariogram is relatively flat indicating little spatial correlation. Considering the marine sand, the nugget is similar but the sill is lower than for the fill. A comparison of the spatial structure of the two units indicates that the fill unit exhibits more spatial correlation than the marine sand based on its larger difference between sill and nugget values. The relatively high nugget value for both units is indicative of a large amount of short-scale variation associated with the data. Since the categories of PGA trigger values are largely based on the density of the sample, the large nugget values for both units are likely associated with the high degree of inherent variability and error associated with blow count measurements, as well as, the large degree of spatial variability in the vertical and horizontal directions. As a result spatial correlation is limited to less than 200 m in the fill unit and there is virtually no spatial correlation in the marine sand. This result is surprising considering that the marine sand is a natural deposit. The flat semivariogram leads to the conclusion that the homogeneous layer assumption is more appropriate for the marine sand than a spatially correlated model. The lower sill exhibited by the marine sand as compared to the artificial fill indicates that the overall variability of liquefaction susceptibility is less. Although the fill semivariogram has a high nugget and high sill, we will use it to interpolate the hazard across the region. The resulting mean prediction will have high uncertainty as a result of the overall high semivariogram values.

Interpolation

The spatial distribution of category values for the artificial fill, alluvial and estuarine sands, and marine sands are shown in Figure 15a, b, and c (respectively). It is apparent that the frequency of very highly and highly susceptible samples is very high in the alluvial and estuarine sands as well as in the artificial fill. In edition, although the sample distribution is spatially variable, there does appear to be some spatial organization. Even in the marine sand with very few samples that are highly, or very highly susceptible, those samples are grouped in the southwestern portion of the study area.

Now that we can see the spatial distribution of the susceptible samples, the regional classification is more clear. In the artificial fill (16% samples are liquefiable for the design earthquake), we expect zones of liquefiable materials scattered throughout the fill unit. The entire unit will not liquefy, but the zones will cover single sites as well as entire city blocks. For the estuarine and alluvial sands, the unit is not pervasive across the site. However, where it exists it is very likely to liquefy (34%) during the design earthquake. Again the zones of material are small but will likely be large enough to impact overlying structures. Finally, the marine sand with a moderate susceptibility (7%) still has zones of collocated liquefiable materials that may impact sites throughout the mapped geologic unit.

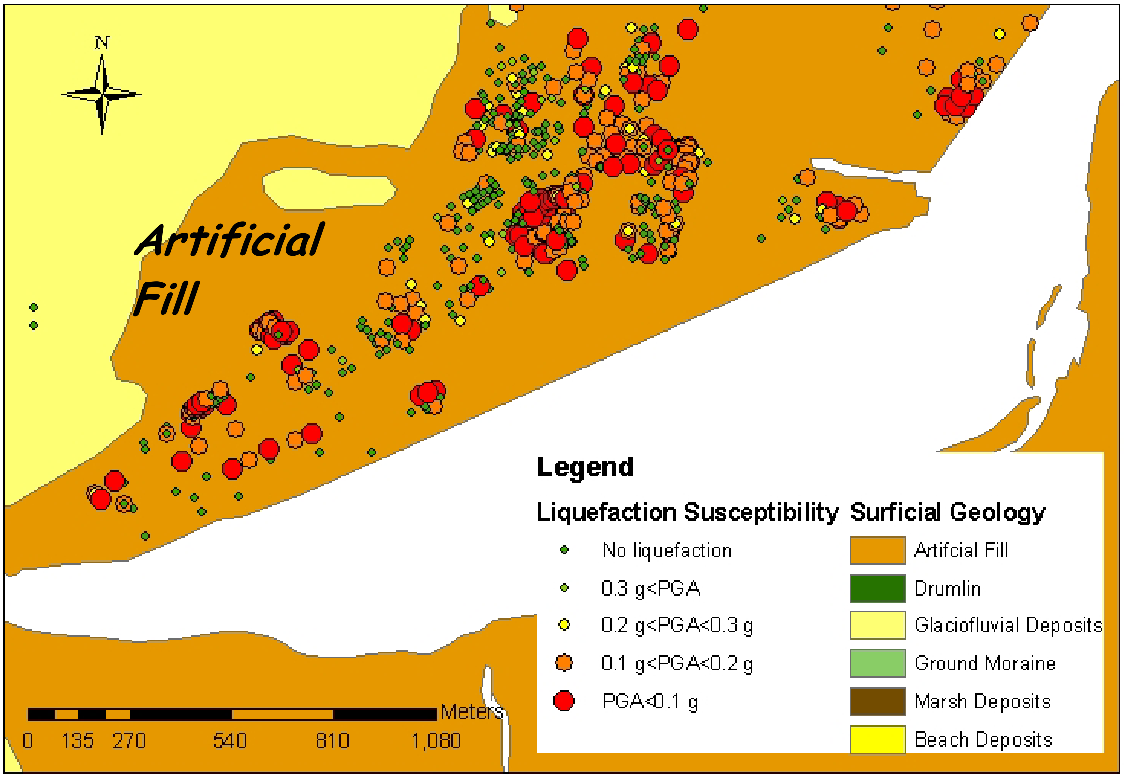


Figure 15 a) Susceptibility category for Artificial Fill

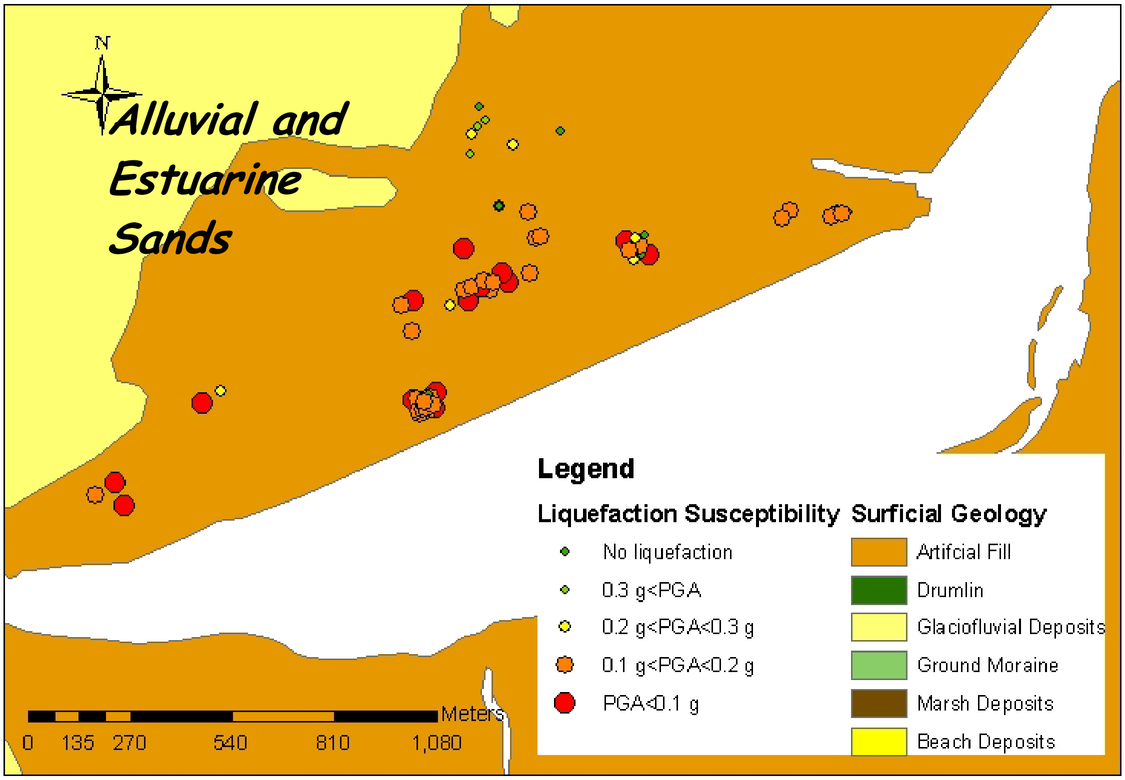


Figure 15 b) Susceptibility category in the Alluvial and Estuarine Sands

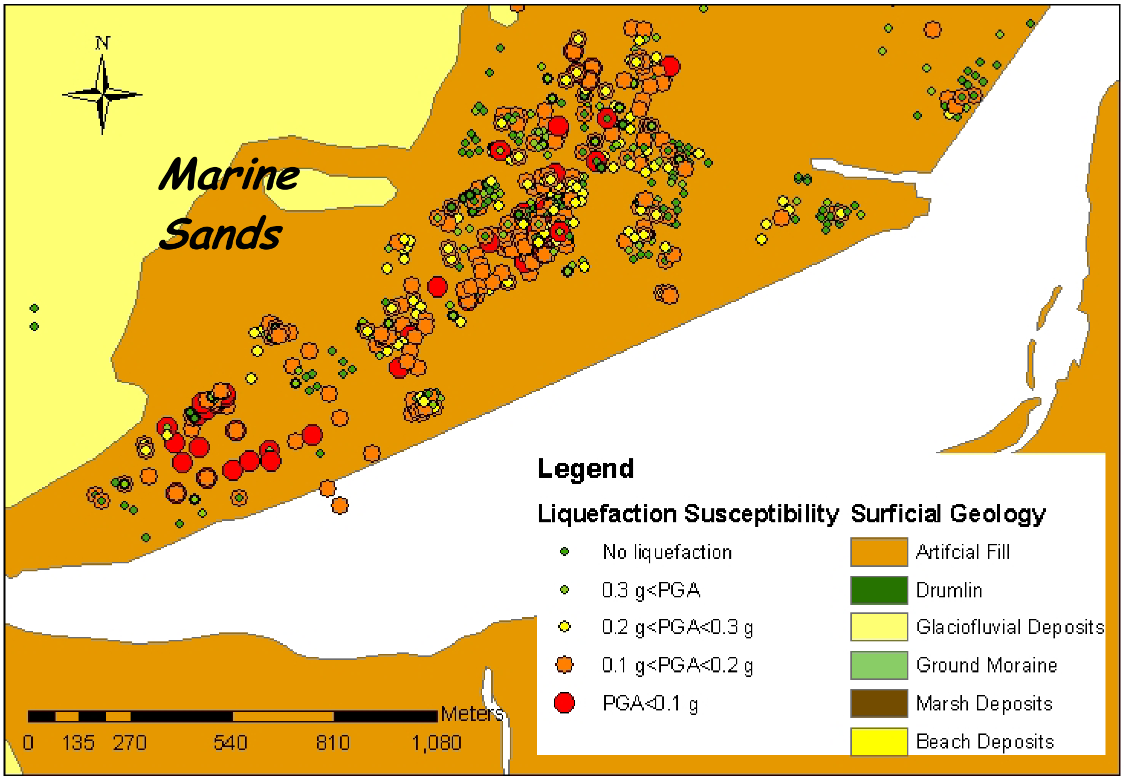


Figure 15 c) Susceptibility category in the Marine Sands

Figure 16 is the resulting map of predicted liquefaction susceptibility categories in the artificial fill using the Ordinary Kriging method. The category associated with the minimum $PGA_{trigger}$ value at each boring location was used in the analysis. Prediction results of the artificial fill indicate that the liquefaction hazard ranges from low to high susceptibility (categories 2, 3, and 4) with a few small areas of very high susceptibility (category 5) or very low susceptibility (category 1). The majority of the areas where categories 1 or 5 are predicted in Figure 18 are due to edge effects of the kriging method and therefore are not deemed reliable. Lower susceptibility exists within the northwestern portion of the site. Zones of high susceptibility exist near the center of the site and in the southwestern region. The spatial pattern across the region is highly irregular; however, the zones of high susceptibility are anywhere from 200 to 500 m across. The susceptible part of the fill is expected to be the deeper portion where the fill has not been as highly compacted.

When comparing Figure 15a and Figure 16, it is important to remember that Kriging tends to smooth maps. A Kriged interpolation is the best linear unbiased estimator; therefore, in order to minimize prediction error, estimates tend towards the mean value. Although we are primarily interested in maximum category values, the interpolated map underestimates the zones of very high or very low susceptibility. Figures 15a through 15c more clearly show areas of high susceptibility.

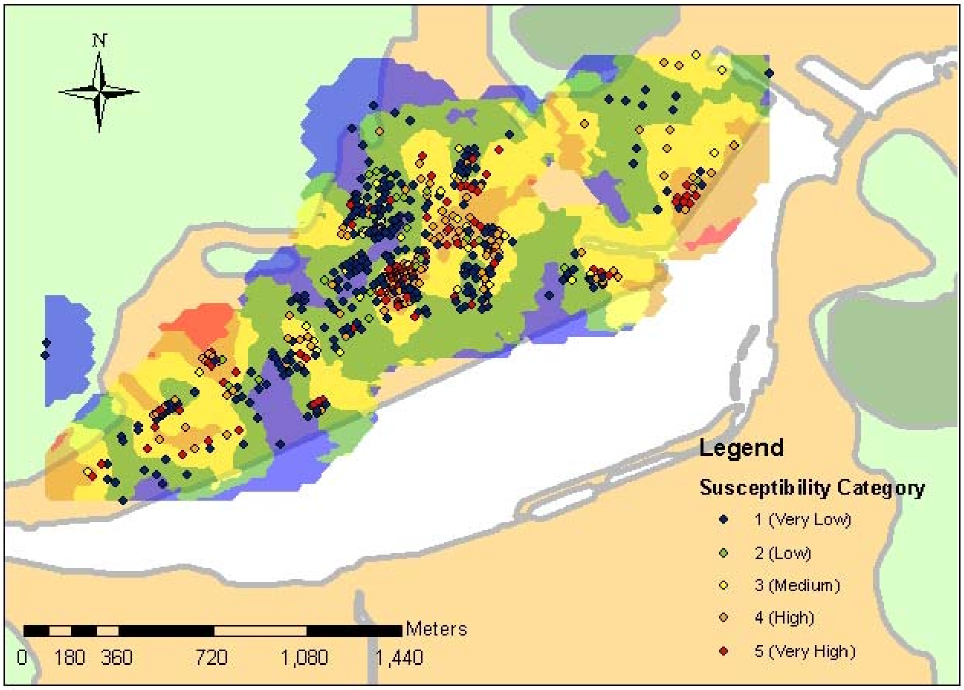


Figure 16. Interpolated map of liquefaction susceptibility for the artificial fill

Concluding Remark for Case Study I

In terms of liquefaction susceptibility in this case study, three distinct units were identified. We examined liquefaction susceptibility using sample blowcounts and sample susceptibility category values. We have attempted to separate the liquefaction susceptibility of a soil sample (Table 2) with the liquefaction susceptibility of a regional geologic unit (Table 5). Our proposed regional mapping criteria are listed in Table 5. The new criteria take into account quantitative results from geotechnical boring data in addition to the surficial geology. These criteria rely on estimates of the distribution of liquefiable soils using either probabilistic or statistical estimates. According to the proposed regional criteria, liquefaction susceptibility is broken into three categories: high, moderate, and low. The categories are associated with an estimated volume percentage of susceptible material. It is important to realize that the estimated volumes are lower than the estimated map area percentages of susceptible material. At this point, we choose the volume percentages because we think an important next step is three-dimensional characterization of susceptible materials (as explored in Case Study 2).

The loosest layer was the alluvial and estuarine sands below the artificial fill. This unit is expected to be highly susceptible with 34% of the samples liquefying with a trigger acceleration of 0.12 g; however, this unit is thin and not pervasive across the site. The artificial fill is also highly susceptible to liquefaction with 16% of the samples liquefiable at the trigger acceleration of 0.12 g. Both the alluvial and estuarine sands and the artificial fill are expected to liquefy in significant zones during the design earthquake. These zones will range in size from a single site to a city block (as seen in Figure 15a, b, and Figure 16). Alternatively, the marine sand has small pockets of susceptible material and is therefore categorized as moderately susceptible. In terms of the samples in the marine sand, only 7% would liquefy with the design level trigger acceleration.

In the above characterizations, we have relied on a dense dataset. When a dense dataset is available, variability of liquefaction susceptibility can be quantified. Unfortunately, this is not often the case. When only a few borings are available to characterize liquefaction susceptibility, a large degree of uncertainty will exist. To characterize liquefaction susceptibility with a limited set of borings, two choices have been examined: 1) estimate probability of finding blowcounts below a limiting value using lognormal distributions and 2) sample percentages based on the design earthquake peak ground acceleration trigger level. An estimate of the lognormal distribution of the corrected blowcounts is sufficiently accurate with only 5 to 10 borings in a unit to determine the distribution of density in the unit; however, when blowcounts are used directly to estimate liquefaction susceptibility, saturation and grain size are not considered and the resulting estimate may be significantly biased. The effects of silty and unsaturated soils will have a significant effect on the liquefiability of the unit and therefore need to be accounted for separately. The alternative is directly estimating the percentage of samples that will liquefy if the design level peak ground acceleration is exceeded. Sample percentages using peak ground acceleration trigger levels are highly uncertain and do not have sufficient accuracy to meet the criteria listed in Table 5. In this case study, the estimates were only consistent when 100 borings or more were used in the estimate. As a result of this difficulty and the fact that we have a very dense data set, we have used sample percentages to quantify the liquefaction susceptibility of the three units in this region.

When dense boring data is available, geostatistical methods provide a means of estimating specific areas of susceptible material. The interpolation in the artificial fill unit resulted in pinpointing several zones of high susceptibility. These zones ranged from 200 to 500 m across. The marine sand deposit in this area showed very little spatial correlation; however, a two-dimensional plot of susceptibility category values demonstrated that the high category values tended to be co-located. The lack of spatial correlation in the semivariogram may be a result of the uniformity of the deposit, the overall variability of the dataset, or the assumptions in the analysis. One disadvantage in the study was the two-dimensional nature of the spatial analysis. The second case study will use three-dimensional geostatistics to determine the effect of this assumption.

5.3 Case Study II – Downtown Boston

The second case study encompasses eight fill regions around Boston. This case study uses the dense dataset of borings collected for the Central Artery/Tunnel project as shown in Figure 17. The 8 fill regions are East Cove, South Boston, South Cove, West Cove, South Bay, Logan Airport, Mill Pond, and Charlestown. The fill history for each of these units was summarized earlier in Section 4.2. The eight fill units were characterized statistically as summarized in Table 6. We briefly explored using three-dimensional geostatistical methods in order to identify potential zones of liquefaction in the fill. Three-dimensional methods provide an advantage over the two-dimensional methods used in the first case-study in that they include the depth explicitly. Using the Kriging method we can build volumetric models of the liquefaction potential of each fill region and quantify the spatial variability of the data used to build the model. We have tested this method by applying it to several liquefaction case studies in the literature including an analysis of the Balboa site (Holzer et al., 1999). Our three-dimensional analysis compared very well with the previous results at the site by Holzer et al. (1999).

Figure 17. Boston Fill Regions and Location of CA/T Soil Borings

				Semivariogram Parameters			
Region	**No. of Liquefiable Samples**	**Total No. of Samples**	**Percentage of Liquefiable Samples**	**N_{160} Range**	**N_{160} Sill**	**Indicator Range**	**Indicator Sill**
East Cove	17	406	4.2%	918	4371	918	0.05
South Boston	306	1814	16.9%	3343	897	3343	0.14
South Cove	31	650	4.8%	2195	3246	2195	0.05
West Cove	13	226	5.8%	657	1109	657	0.06
South Bay	82	1058	7.8%	2217	1546	2217	0.07
Logan Airport	144	1789	8.0%	5169	1194	5169	0.06
Mill Pond	116	1257	9.2%	1351	1809	1351	0.08
Charlestown	76	731	10.4%	2331	1037	2332	0.08

Table 6. Summary of Quantities of Liquefiable Samples and Semivariogram Parameters for Boston Study Fill Regions

For the eight fill regions, the range of percent of liquefiable samples is 4.2% in East Cove to 16.9% in South Boston. Most of the regions cluster between 5% and 10%. In terms of spatial variability, the semivariograms for corrected blowcounts have a range from 657 ft in West Cove to 5169 ft in the Logan Airport Fill. The larger range values indicate a broader extent of spatial correlation and are generally associated with larger areas. The sill values range from 897 in South Boston and 3246 in South Cove. A lower sill value is indicative of an overall lower variability in corrected blowcount values. The South Boston fill is unique in that it has a large degree of spatial correlation (large range) and overall low variability (low sill). As compared to other fill units (i.e. East Cove) with lower ranges and higher sill values, interpolation of liquefaction hazard in the South Boston fill should provide reliable estimates.

Using three-dimensional geostatistics, we were able to visualize the potentially liquefiable soil volumes in the fill regions of Boston. Figure 18 shows a cross-section through a three-dimensional interpolation of corrected blowcounts in the South Boston fill region. The low blowcount values are clustered in a laterally extensive layer approximately 12 to 15 feet below the ground surface. The same analysis was completed for the other seven fill regions in order to identify continuous volumes of liquefiable materials. Large volumes of susceptible soils were identified in Mill Pond and Logan Airport as well. A relatively loose layer of soil exists approximately 15 feet below the ground surface in the Mill Pond fill region. At Logan airport, the loose layer is approximately 10 feet below the ground surface and is laterally extensive. Each of the other fill regions had isolated volumes of low blowcounts.

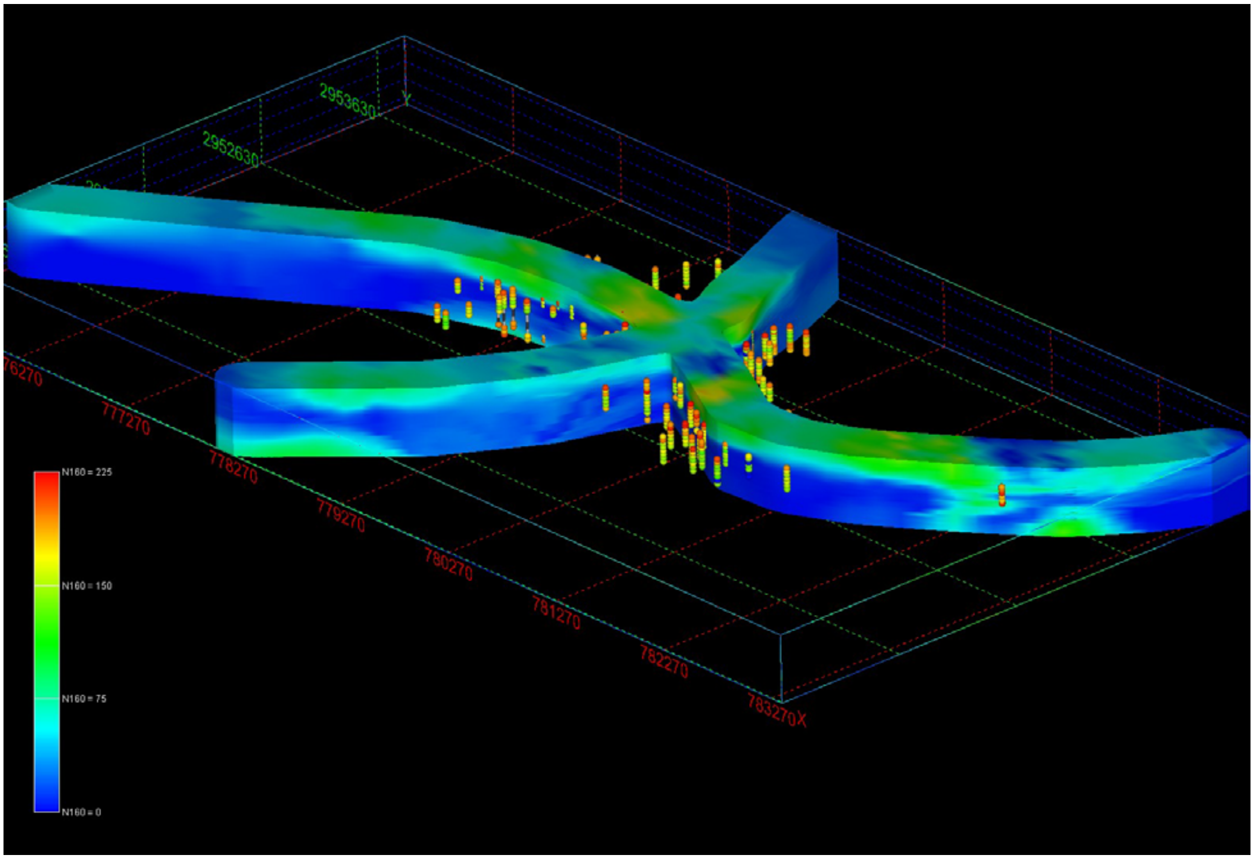


Figure 18. Fence diagram through three-dimensional prediction of corrected blowcounts in South Boston. Hot colors indicate high SPT blowcounts, or dense soils, while cool colors represent low blowcounts.

As part of an ongoing research initiative, we are developing a three-dimensional analysis method for assessing liquefaction hazard using the geotechnical boring data collected for this study. The following is a brief description and some preliminary results from this new initiative. We are looking at indicator values of liquefaction susceptibility – either a sample is liquefiable (1) or not liquefiable (0). These values are then used in the geostatistical interpolation which results in a prediction of the probability of liquefaction. In terms of interpolation uncertainty, we are using an estimate of confidence in the prediction. A confidence of 80% (with 0.15 tolerance) refers to 80% confidence that the predicted mean value is within 0.15 units of the predicted probability of liquefaction. We can, therefore, isolate interpolated volumes of liquefiable materials that have been predicted with a confidence of at least 80%. Figure 19 presents a cross-sectional slice through the three-dimensional results of this calculation for South Boston. For a probability of liquefaction equal to 0.7, with a factor of safety against liquefaction equal to 1.2, we predict that this liquefiable volume is approximately 8 to 30 feet thick, 1,500 feet long, and 300 feet wide.

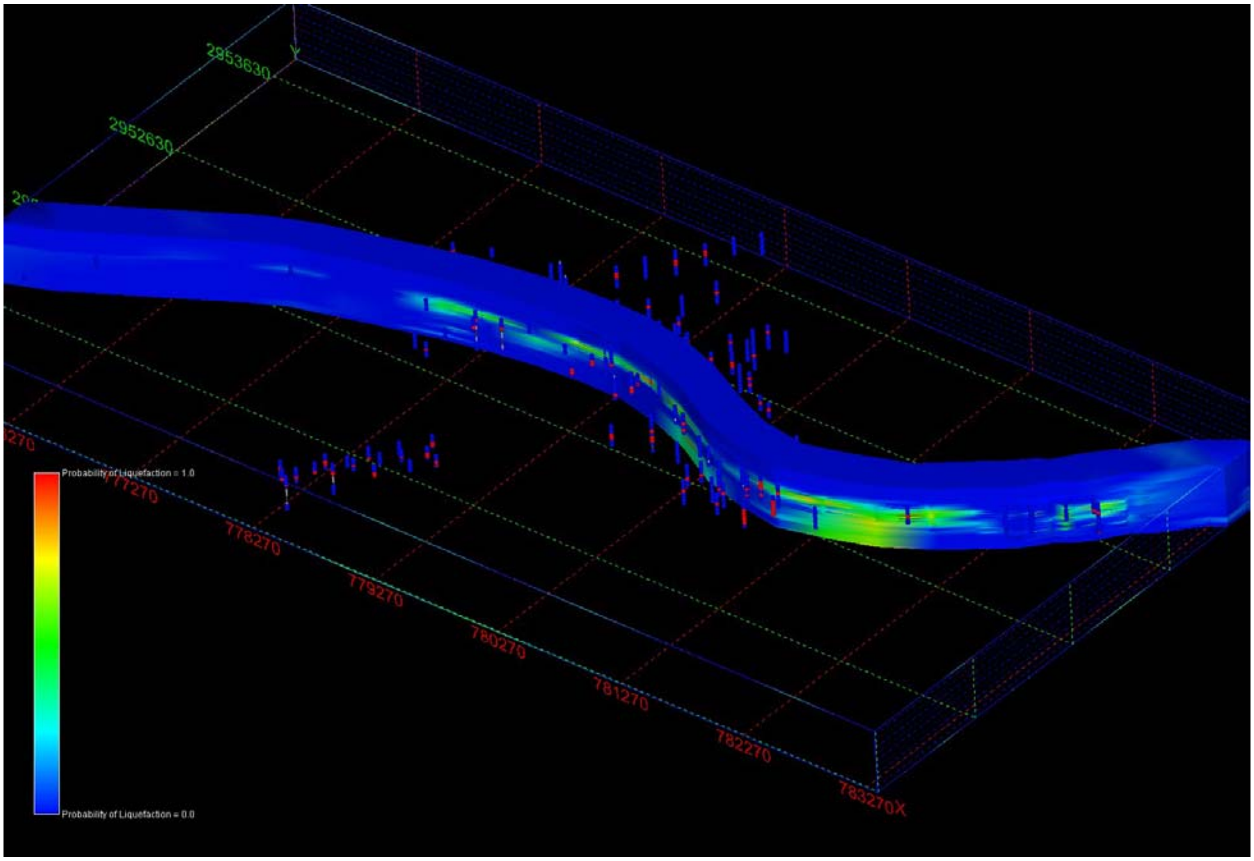


Figure 19. Slice through model of probability of liquefaction for South Boston. Hot colors represent high liquefaction probability.

Figure 20 shows the location of volumes of liquefiable soil (probability of liquefaction of 0.7) on a two-dimensional map of South Boston. Only volumes that can be estimated with at least 80% confidence are shown. As a result the interpolations do not extend much beyond the extent of the original dataset. The locations of boring logs used in the estimation are shown as blue dots in the figure. The extent of liquefiable soils in South Boston can be clearly seen in the figure.

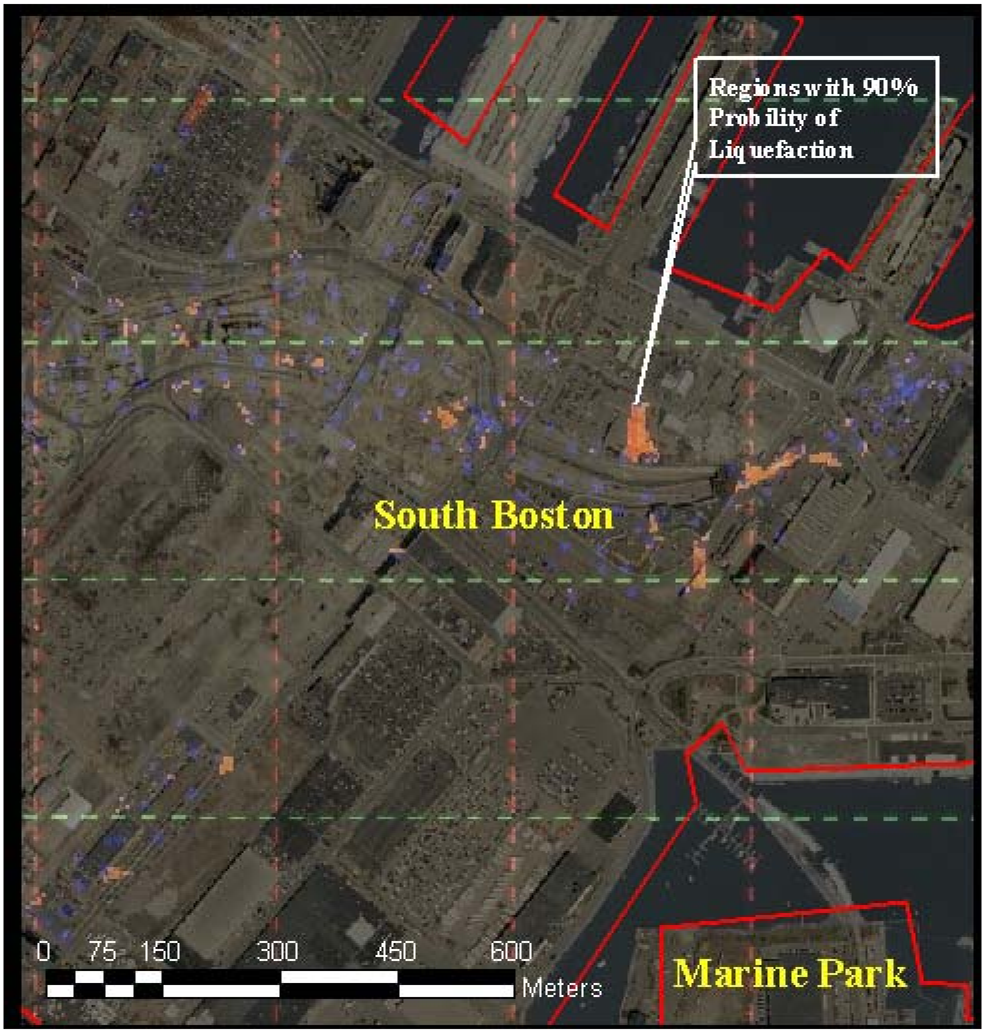


Figure 20. Top view of model of probability of liquefaction for South Boston. Probability of liquefaction = 0.9, Confidence = 80%, Tolerance = 0.15

As a result of the three-dimensional analyses, we assign a high hazard to the South Boston fill, the Mill Pond fill, and the Logan Fill. A close-up of the identified zones of high hazard in Mill Pond is shown in Figure 21. It is important to recognize that liquefiable zones are only identified within the extent of the boring data. The other fill units are moderate to high hazard. During the design earthquake, liquefaction may develop for areas as large as building sites or even city blocks; however, liquefaction will not likely be pervasive across the entire region. Therefore, site-specific analyses are still recommended.

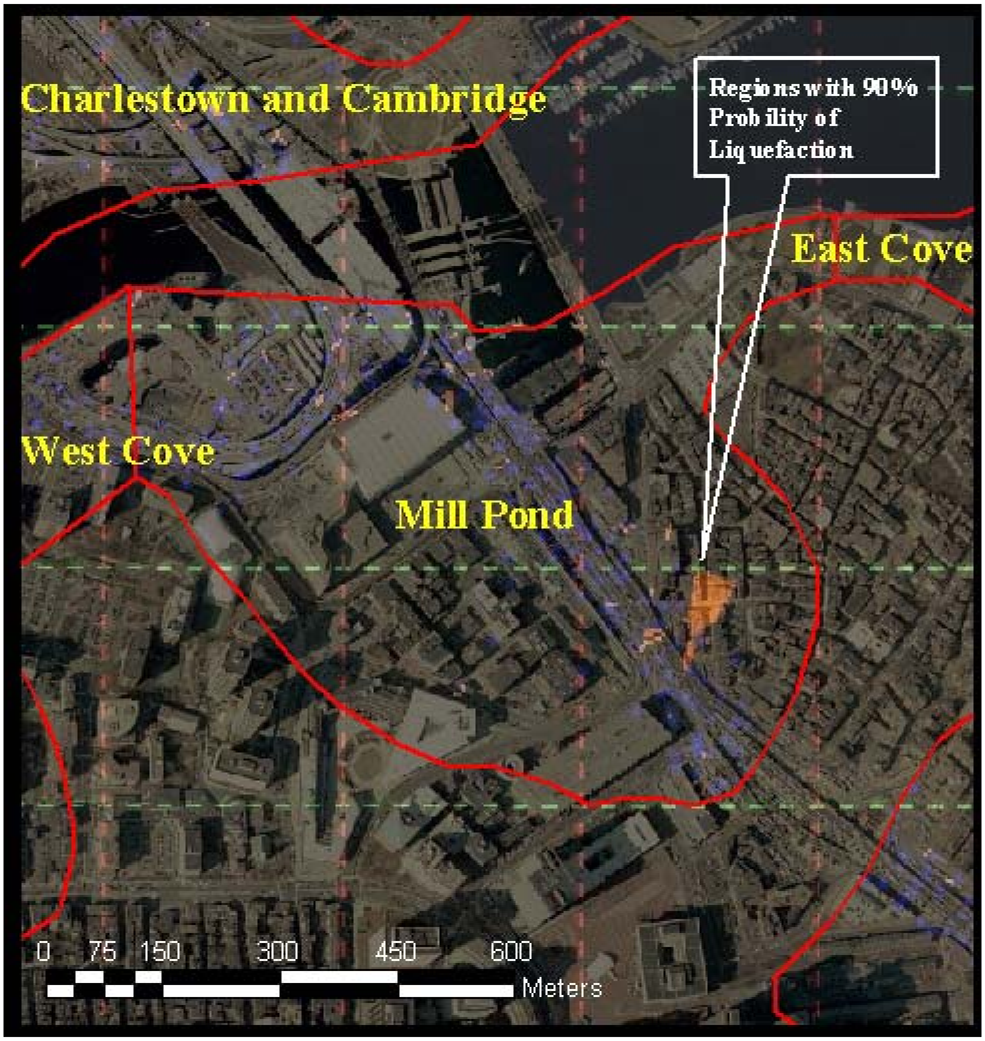


Figure 21. Map of lateral extent of theoretically liquefiable soil for Mill Pond fill region. Blue dots indicate locations of borings used in the study. The probability of liquefaction for the mapped regions is 0.9. The model confidence = 80% with a tolerance of 0.15 units.

6.0 REGIONAL LIQUEFACTION SUSCEPTIBILITY ANALYSES & MAPS

Table 7 shows the proposed mapping criteria developed in this study (from Case Study I and II). The first column is the recommended susceptibility category. The second column is a qualitative description of the extent of liquefaction associated with each susceptibility category. This qualitative estimate was developed from the geostatistical interpolations performed in the case studies. The case studies were performed in regions of artificial fill over a natural marine deposit and therefore we did not geostatistically interpolate zones of liquefiable materials in any of the other geologic units presented herein. The extents presented are therefore speculations based on an extrapolation of the results from the case study combined with the sample distributions from each geologic distribution presented below in Table 7 and Figure 24. The third column in the table presents the criteria for geotechnical data to determine liquefaction susceptibility. As discussed in the case studies, the best estimate of this would result from estimating a lognormal distribution for blowcount values (if saturation and soil type are well known and can be accounted for). In most cases this is not feasible, therefore, sample percentages based on whether or not the sample will liquefy during the design earthquake are appropriate. If sample percentages are used, large estimate error is expected unless the sample sizes are very large (>100 borings). The proposed criteria should be modified as more quantitative data are collected for regional liquefaction mapping projects (Baise has proposed a follow-up NEHRP project for FY 2005 to solidify these criteria). The final column in Table 7 shows how the proposed hazard categories relate to the geologic units in Boston.

Hazard Category	Extent of Liquefaction	Predicted volume of liquefiable materials in percentage	Geologic Units (in Boston)
High Hazard	Extensive liquefaction across the geologic unit. Site-scale liquefaction to regional-scale liquefaction	>15%	Artificial Fill, Marsh Deposits, Alluvial and Estuarine Deposits (only in subsurface)
Moderate Hazard	Sparse zones of liquefaction potential. Zones are on the site-scale	<15% and >5%	Marine Sands (only in subsurface)
Low Hazard	Few to no zones of liquefaction potential. Any liquefiable soils are isolated.	<5%	Glacio-fluvial Deposits (outwash, eskers, etc), Glacial Till, Bedrock

Table 7. Proposed regional hazard mapping criteria based on cumulative probabilities of lognormally transformed corrected blowcounts or sample percentages.

The liquefaction hazard criteria presented in this report does not explicitly describe expected deformations resulting from liquefaction (i.e. settlements, lateral spreading, etc.) which is an important next step and would depend on thickness of susceptible unit, depth to susceptible unit, lateral extent of susceptible unit, topography, and nearby structures. Rather, the maps produced using this criteria are meant to characterize the spatial extent of liquefiable materials. This information can be used for the planning of detailed explorations for a site.

Using the results from the two case studies, we applied our new regional mapping methodology to the study area. The surficial geology mapping resulted in six geologic units: artificial fill, marsh deposits, glaciofluvial deposits, drumlin till, ground moraine till, and beach deposits. The artificial fill unit near downtown Boston was the only geologic unit that was densely sampled; therefore, the susceptibility of the artificial fill will come directly from the case studies. The geotechnical data were only sparsely collected over much of the study region; therefore, the liquefaction susceptibility will rely heavily on the surficial geology mapping presented in Section 4. These categories agree largely with the susceptibility of the units as determined from geologic criteria

In order to determine the susceptibility according to geotechnical data, all samples in each of the six surficial geology categories were queried from the database. The resulting collections of samples include all soil samples taken within the geographic confines of that surficial geologic unit. The category value is used to present susceptibility because it appropriately handles unliquefiable materials with low blowcounts (clays, unsaturated sands). The distributions of susceptibility categories for each unit are shown in Figure 22. The artificial fill distribution is not shown.

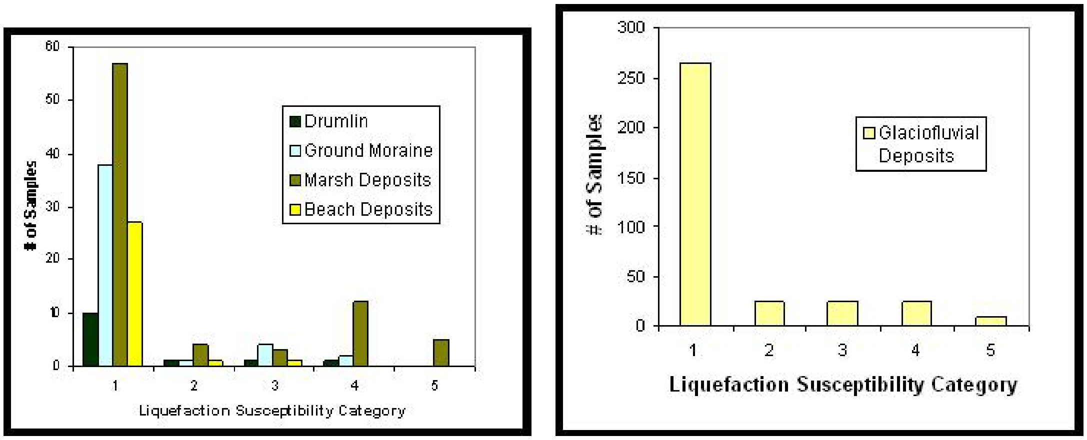


Figure 22. a) Histogram of susceptibility category values for Drumlin, Ground Moraine, Marsh Deposits, and Beach Deposits. b) Histogram of susceptibility category values for Glaciofluvial Deposits.

Table 8 describes the sample populations in each of the six geologic units in the regional study area. The glaciofluvial deposit has 347 samples and the marsh deposits are represented by 81 samples in the database. The three other units are sampled to a lesser degree. According to the results shown, 7.5% of the samples in the marsh deposits are susceptibility to liquefaction in the design earthquake (which is similar to the artificial fill). Only 3.2% of the samples in the glaciofluvial deposits are susceptible to liquefaction for the design earthquake. In terms of predicted map area, the artificial fill has 29% of borings with some susceptible soils. The marsh deposits and glaciofluvial deposits have 22% and 12% of borings with some susceptible material, respectively. As compared to the volume estimates which may seem small, the area estimates show that over 20% of the map area in the marsh and fill deposits has some susceptible soils. In the glaciofluvial deposits 12% of the map area as compared to 3% of the volume is susceptible. In the glaciofluvial layer, 11 samples were liquefiable across 9 borings; therefore, the susceptible material is limited in thickness and likely limited in extent.

As we have shown in the case studies, soil in the artificial fill layer in Boston is spatially variable and heterogeneous. Therefore, the susceptible soils are not always part of continuous zones. The density of the dataset did not allow us to evaluate in detail the spatial variability in the marsh or glaciofluvial deposits. Geologically, we expect that the marsh deposits will be more uniform than the artificial fill. The glaciofluival deposits are locally heterogeneous, but probably more homogeneous than the highly variable fill unit. The other three units did not have any samples that were susceptible to the design earthquake. The beach deposits have surprising low susceptibility. After close examination of the 29 samples in the beach deposit, none of the samples were taken in an actual beach deposit. Most were taken through artificial fill encountering miscellaneous dense materials.

	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	9898	1727	7.6%	29%
Marsh Deposits	81	18	7.4%	22%
Glaciofluvial Deposits	347	78	3.2%	12%
Drumlin***	13	6	0%	0%
Ground Moraine***	45	16	0%	0%
Beach Deposits***	29	8	0%	0%

Table 8. Distribution of susceptible samples by geologic unit (includes all samples)
[*** = small sample]

In addition to the statistics presented above, Figure 23 through 26 show the spatial distribution of the samples in each geologic unit. Each pie chart shown in the figure represents the liquefaction susceptibility of all soil samples taken in that boring (using liquefaction susceptibility category values).

Very few samples were taken in the drumlin deposit (one boring is shown in Figure 23). Based on the deposition history of a drumlin deposit, the material is expected to be very dense and not susceptible to liquefaction. The 13 samples from the drumlin deposit confirm this expectation (0% liquefiable). Therefore, all drumlin deposits will be categorized as low hazard.

Several geotechnical borings in the glaciofluvial deposits are shown in Figure 23 and Figure 24. Based on the depositional history, the glaciofluvial deposits are expected to be sand and gravel layers with some silt and cobble interbeds, with variable density and thus resistance to liquefaction. The results from the geotechnical data are variable (11 out of 347 samples are liquefiable and 9 out 78 borings have liquefiable material). Some borings have only nonliquefiable samples, while others have several samples that would liquefy for a larger earthquake than the design earthquake (PGA>0.2g). The glaciofluvial deposits will be mapped as low hazard. If the design earthquake was altered, the hazard might increase. The liquefiable samples are isolated and therefore, we do not expect large, continuous zones of liquefiable materials.

Several geotechnical borings in the marsh deposits are shown in Figure 24 (west of Boston). The marsh deposits vary from silty to sandy soils. Most of the soils in the marsh deposits are loose and saturated. The silty soils are not liquefiable; however, the sandy soils tend to be liquefiable in our design earthquake. The marsh deposits will thus be mapped as high hazard.

Very few samples were taken in the ground moraine deposit. The ground moraine deposit is generally a thin glacial deposit over bedrock. These deposits are expected to be dense to very dense. This deposit will be mapped as low hazard.

The few samples in the beach deposit did were not representative of the sandy soils expected in a Holocene beach deposit. Holocene beach deposits are expected to be loose, saturated sandy deposits and are highly susceptible to liquefaction. The beach deposits will therefore be mapped as high hazard.

Finally, the artificial fill will be mapped as high hazard. In both case studies (Cambridge and Boston), large continuous zones of liquefiable materials were located. The entire regions will not liquefy. See the detailed case studies to identify the spatial distribution of liquefiable materials in the artificial fill. Figure 25 shows the distribution of liquefiable samples in the artificial fill in downtown Boston (Mill Pond area on left and East Cove to right). The Mill Pond region has more liquefiable materials than East Cove. Figure 26 shows the distribution of liquefiable samples in Back Bay. The Back Bay artificial fill region is highly susceptible to liquefaction during the design earthquake (as illustrated by the red and orange samples). The spatial

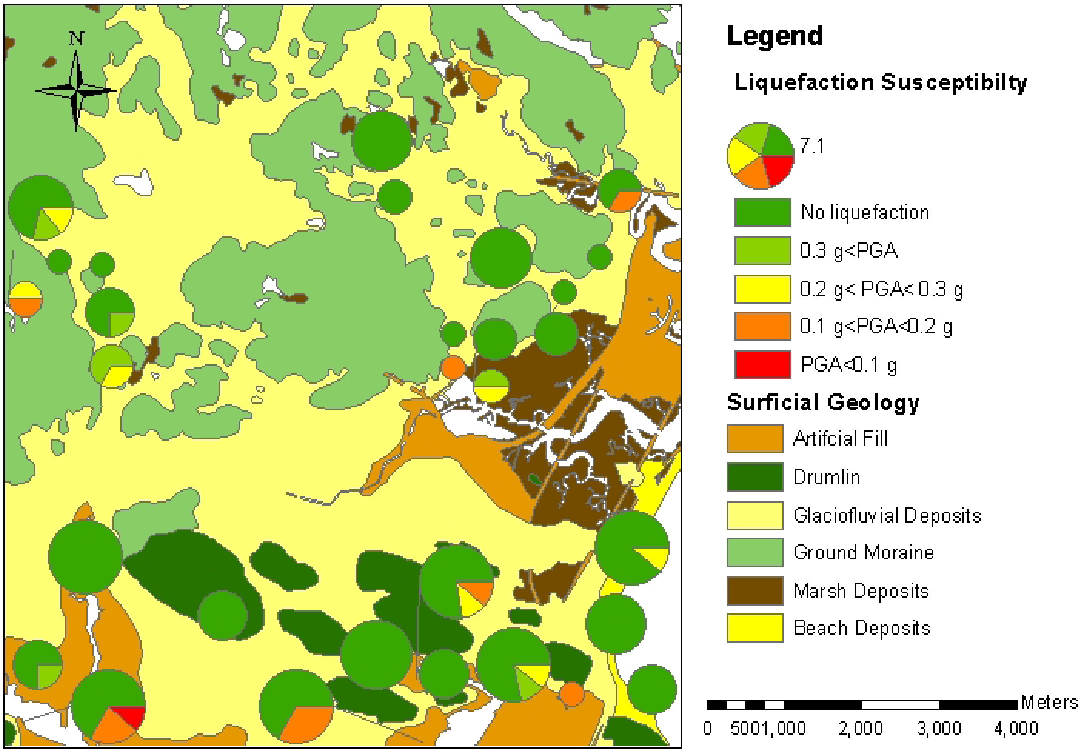


Figure 23. Summary plots of liquefaction susceptibility by sample in the drumlin and glaciofluvial units north of Boston

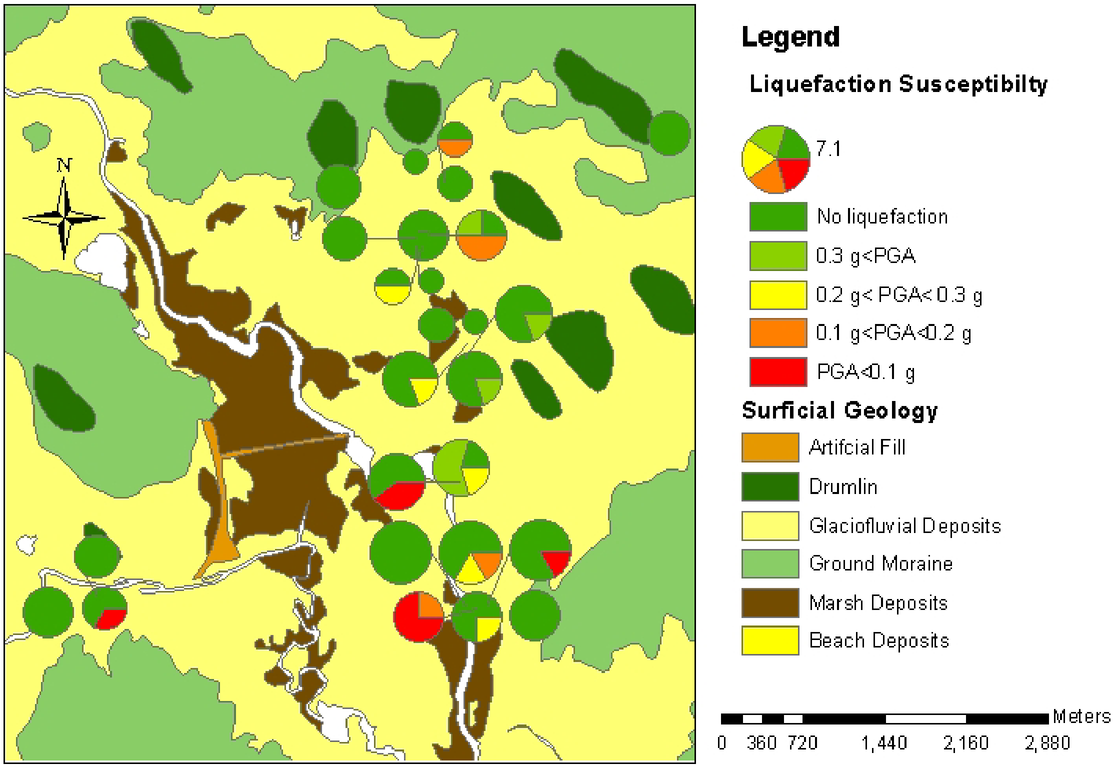


Figure 24. Summary plots of liquefaction susceptibility by sample in the glaciofluvial and marsh deposits southwest of Boston

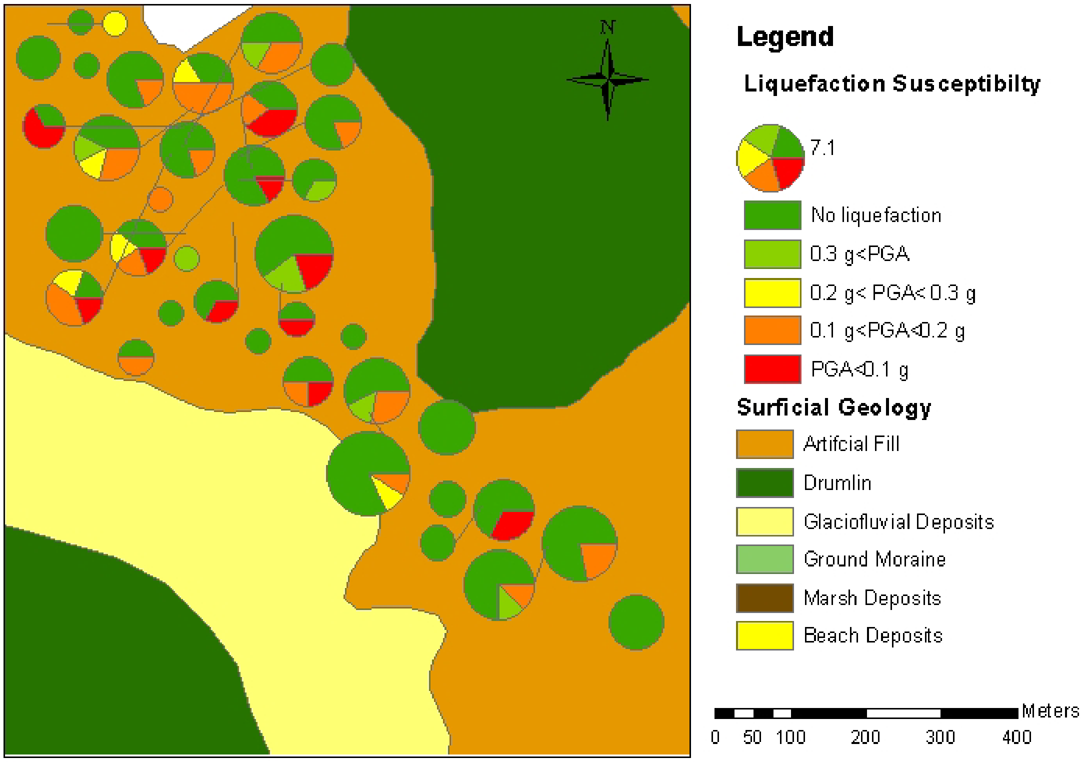


Figure 25. Summary plots of liquefaction susceptibility by sample in the artificial fill in downtown Boston

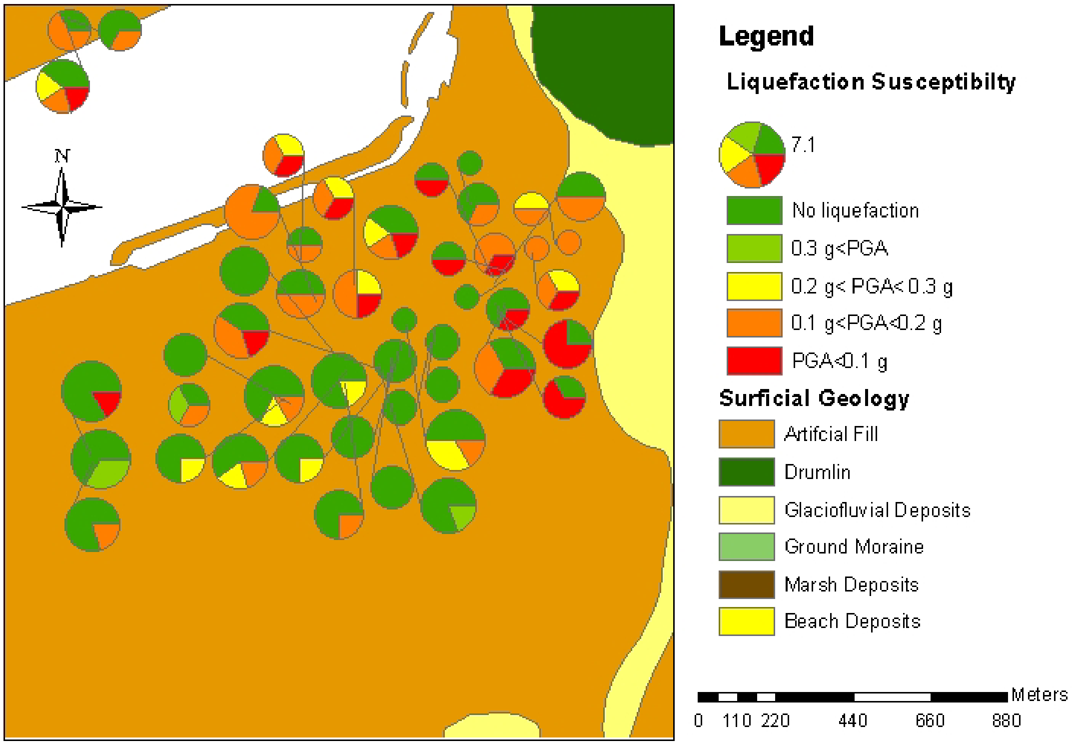


Figure 26. Summary plots of liquefaction susceptibility by sample in the artificial fill in the Back Bay of Boston.

distribution of liquefiable materials is highly variable in different fill regions depending on the fill and construction history of the area. It should be noted that some regions of fill, particularly those underlying modern highways and developments, were most likely adequately compacted during construction and designed to be resistant to liquefaction. However, because we lack quantitative geotechnical data from most of these site-specific project areas, we map them like the other nonengineered fill as high susceptibility.

The liquefaction hazard map for Boston and surrounding communities is shown in Figure 27, and in Plates 9 - 16. As shown in the figure, the high susceptible regions are focused around downtown Boston where most of the historic artificial fill is located. Although the artificial fill is mapped as high hazard, the material is highly heterogeneous and varies from very loose to very dense. Liquefaction will not be pervasive across the region; however, large zones (covering entire city blocks) are expected. It is important to remember that the downtown Boston area has been extensively developed and it is conventional for construction projects to remove the historic fill before construction. Therefore, the hazard is most likely reduced in areas of modern construction. However, roadways and utilities (lifelines) are still likely at risk.

7.0 DISCUSSION

The regional liquefaction mapping criteria presented in Table 7 is based on the results of the two case studies in Section 5 and is preliminary in nature. The proposed criteria provide a method to quantify the liquefaction hazard associated with geotechnical data (liquefaction susceptibility based on blowcounts, soil information, and the design earthquake) by regional geologic unit. The proposed cutoff values for percent of liquefiable samples are preliminary and should be refined as more data over a wider range of geologic environments is collected. In addition, the proposed cutoff values and extent of liquefaction should be validated with case histories of liquefied regions in past earthquakes. Baise has a submitted a NEHRP Proposal for FY05 to continue this research and validate the regional liquefaction mapping guidelines proposed herein.

When the proposed mapping criteria were applied to Boston (Section 6), the primary shortcoming was lack of data. The results of the case studies indicated that dense data were needed to characterize the distribution of liquefiable samples by geologic unit with sample percentages. The density of geotechnical data was not sufficient except for in the downtown artificial fill units. For this study, the most susceptible unit appears to be the artificial fill; therefore, only a limited effort was made to collect geotechnical data over greater Boston. Therefore, the maps are predominantly based on surficial geology.

Based on the case studies in the artificial fill units in downtown Boston and Cambridge, liquefaction susceptibility can be extremely variable across a single unit. Even when the unit was a natural deposit (the marine sand underlying the artificial fill in Cambridge), susceptibility varied from high to low across the unit. Therefore, the proposed mapping criteria are based on extents of liquefaction: low to high hazard categories are associated with varying extents of liquefaction (see Table 7). With the proposed criteria, even a low hazard unit may have a few

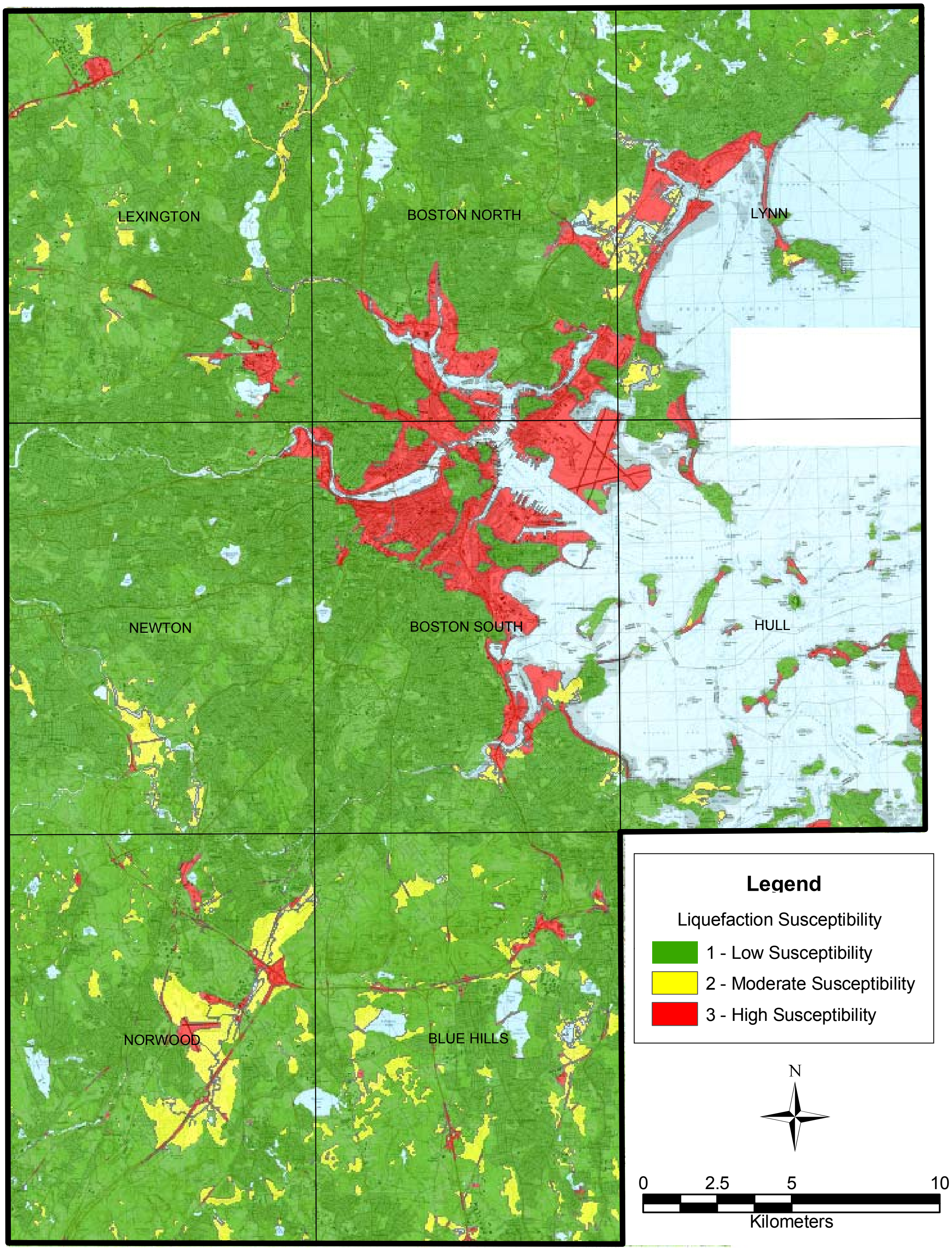


Figure 27. Liquefaction susceptibility of the Boston, Massachusetts metropolitan area.

pockets of liquefiable material. The proposed criteria, therefore, accounts for the variability of soils and properly characterizes the distribution of liquefiable soil within a geologic unit.

In greater Boston, only the artificial fill units and the beach deposits are mapped as high hazard for liquefaction. The beach deposit characterization is based solely on the surficial geology. Beach deposits are expected to be loose, saturated sands and therefore at risk for liquefaction during an earthquake. The artificial fill unit in downtown Boston and in Cambridge has been densely sampled. The liquefaction susceptibility is spatially variable across the artificial fill unit and includes many continuous zones of liquefiable material. As stated in Section 6, it is important to remember that the downtown Boston area has been extensively developed and that it is conventional for construction projects to remove the historic fill before construction. Therefore, the liquefaction hazard is most likely reduced in areas of modern construction. Roadways and utilities (lifelines) are still likely at risk.

8.0 CONCLUSIONS

We have developed a new regional liquefaction mapping criteria presented in Table 7 and applied it to liquefaction hazard maps for greater Boston. The proposed mapping criteria are based on the results from two case studies performed in the artificial fill units and underlying natural deposits in downtown Boston. The proposed 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 proposed mapping criteria is to provide a hazard class that accounts for the variability of geologic materials and the complete distribution of liquefiable materials within a regional geologic unit.

We have assembled surficial geology maps for the greater Boston area as shown in Figure 2 and in the enclosed Plates 1-8. The surficial geology maps were developed from existing high-quality, large-scale, published maps (the Norwood: Chute, 1966, and Blue Hills: Chute, 1965, and for portions of the Boston North and Lexington quadrangles: Chute, 1959), smaller scale maps of the entire study area (e.g. Thompson et al., 1991; Woodhouse et al., 1991; Kaye, 1978), as well as by field reconnaissance mapping using field exposures and geomorphological interpretation.

To complement the surficial geologic maps, we assembled an electronic database of geotechnical data from 2963 test borings. The geotechnical data include stratigraphy, soil sample description, soil type, groundwater level, and SPT blowcount. Although the data are concentrated in the downtown area, the distribution covers the entire study region. The SPT blowcount data were analyzed for susceptibility to liquefaction according to standard procedures (Youd et al., 2001).

Using the proposed mapping criteria, the surficial geology maps, and the geotechnical data, we prepared liquefaction hazard maps for the greater Boston area. The resulting liquefaction maps are shown in Figure 29 and Plates 9-16. These maps are appropriate for the design earthquake for Boston, MA (M6.0 and PGA=0.12 g). Artificial fill and beach deposits are mapped as high hazard. Marsh deposits are mapped as moderate hazard. Marsh deposits are loose deposits of silts and sands. The silty soils ware not liquefiable and the sandy soils tend to be liquefiable during the design earthquake. Glaciofluvial, ground moraine, and drumlin deposits are mapped as low hazard.

9.0 PUBLICATIONS, CONFERENCE PRESENTATIONS, AND STUDENT THESES ORIGINATING FROM THIS RESEARCH

Baise, L.G., Higgins, R.B, and Brankman, C.M., Regional Liquefaction Hazard Mapping. In preparation. To be submitted to ASCE Journal of Geotechnical and Geoenvironmental Engineering.

Brankman, C.M., Baise, L.G., Higgins, R.B, and, Dawson, K.M. Liquefaction Hazard Maps for Boston, Massachusetts. In preparation. To be submitted to Journal of the Association of Engineering Geologists.

Brankman, C.M., Baise, L.G., and Brown, R., 2002, Assessment of Liquefaction Susceptibility of Holocene Sediments and Artificial Fill in Boston, Massachusetts [abstract], Geological Society of America Abstracts with Programs, pp. 519.

Higgins, R.B., Baise, L.G., and Brankman, C.M. (2003) Liquefaction Hazard Mapping in Greater Boston, MA, *12th PanAmerican Conference on Soil Mechanics and Geotechnical Engineering and 39th U.S. Rock Mechanics Symposium*.

Dawson, K.M., (2004) Three-dimensional Liquefaction Hazard Analyses in Boston, Massachusetts, M.S. Thesis, Tufts University.

Higgins, R.B., (2003) Geostatistical Analysis of Liquefaction Hazards in Cambridge, Massachusetts, M.S. Thesis, Tufts University.

The subsurface data collected over the course of these investigations is available to interested individuals. Please contact Laurie Baise (laurie.baise@tufts.edu) for an electronic copy of the database. GIS files of the surficial geology and the liquefaction hazard maps are also available to interested researchers and other user groups.

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Liquefaction Hazard Mapping in Boston, Massachusetts: Collaborative Research with William Lettis & Associates, Inc., and Tufts University

Grant Award No. 02HQGR0036 and 02HQGR0040

Laurie G. Baise
Department of Civil and Environmental Engineering
Tufts University
113 Anderson Hall, Medford, MA 02155
phone: 617-627-2211 fax: 617-627-3994 email: laurie.baise@tufts.edu
webpage: http://ase.tufts.edu/cee/faculty/baise/bio.asp

Charles M. Brankman
William Lettis & Associates, Inc.
1777 Botelho Drive, Suite 262, Walnut Creek, CA 94596
phone: 925-256-6070 fax: 925-256-6076
email: brankman@lettis.com webpage: http://www.lettis.com
now at: Department of Earth and Planetary Sciences, Harvard University
20 Oxford Street, Cambridge, MA 02138
phone: 617-495-0367 fax: 617-495-7660
email: brankman@fas.harvard.edu webpage: http://structure.harvard.edu

Program Element I: Products for Earthquake Loss Reduction
Keywords: Liquefaction, regional seismic hazard, surficial deposits, site effects

Non-technical summary:

We used geologic mapping and geotechnical boring data to develop maps delineating zones of susceptibility to earthquake-induced liquefaction in the Boston, Massachusetts area. Geologic mapping was used to define the distribution and composition of soils throughout the region. We then compiled a database consisting of almost 3000 geotechnical borings, which allowed a detailed examination of these soils in the subsurface. By exploring the statistics of these data, we were able to define zones that may be susceptible to liquefaction during large earthquakes, and develop criteria to extend these calculations to the larger area. We conclude that several regions of artificial fill within the downtown Boston area are susceptible to liquefaction. The artificial fill unit is highly variable. All regions of artificial fill will not liquefy; however, substantial zones in the fill (from the size of one building to the size of several city blocks) may liquefy during an earthquake. Marsh, alluvial, and beach deposits in the greater Boston area are also susceptible to liquefaction during an earthquake. The glacial deposits have a low susceptibility to liquefaction.