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

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Program Element I: Products for Earthquake Loss Reduction
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Annual Project Summary and Progress Report
November 1, 2002

Investigations Undertaken:

This project is a two-year detailed study to characterize the surface and subsurface distribution and geotechnical properties of potentially liquefiable sediments and artificial fill in the City of Boston, Massachusetts. The proposed 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 is underlain by unconsolidated, granular Holocene alluvial deposits and extensive regions of artificial fill that, when saturated, are susceptible to liquefaction during seismic loading. Liquefaction-related features were documented within 30 miles of Boston during the 1727 and 1755 events. Accurate, detailed maps of liquefaction susceptibility will considerably improve the assessment of liquefaction hazards and allow communities to better plan and mitigate the effects of liquefaction on the built environment.

We utilize a multi-disciplinary approach that includes Quaternary geologic mapping and geotechnical analyses to determine liquefaction susceptibility, and geostatistical techniques to reduce uncertainty in areas of sparse data. We have begun to compile a database which currently includes over 900 geotechnical boreholes in order to characterize the liquefaction susceptibility of subsurface units. These data are complimented with published geologic maps, and aerial photographic interpretation. Liquefaction triggering ground motion threshold levels will be determined using borehole data, where available, or by a combination of a decision tree and criteria matrix that we have developed in collaboration with the California Division of Mines and Geology (DMG) for previous liquefaction studies. The spatial uncertainty of the assembled database is in the process of being quantified with geostatistical techniques, using a semi-variogram to characterize the spatial uncertainty and Kriging methods to interpolate at unsampled locations.

Results:

Work to date has primarily involved the following elements: 1) development of a subsurface database, 2) determination of the sequence, extent, and properties of the fill, 3) Quaternary geologic mapping, and 4) assessment of groundwater level. Work has also begun on 5) updating the liquefaction assessment calculations to include the state of the art methodology, and 6) evaluating the spatial statistics of the database to assess uncertainty. We have focused the projects first year s efforts on the South Boston USGS 7.5 Minute Quadrangle as shown in Figure 1.

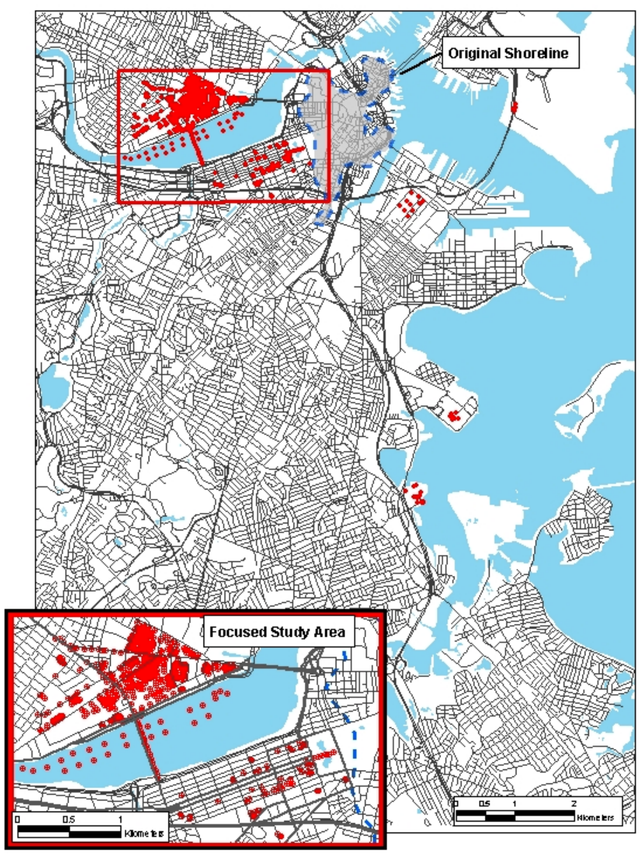

Figure 1 - Study Area and Subsurface Exploration Plan

Subsurface Database

In order to characterize the subsurface conditions, a database of subsurface information is currently being compiled from a vast array of explorations conducted within the Boston area over the past several decades. To date, over 900 test boring logs have been collected from both public and private entities. Additional data is currently being collected and compiled for this project. Figure 1 shows the approximate locations of the test borings entered into the database thus far. As shown, most of the data collection has been focused in the highlighted region around the Charles River including the filled portions of Boston and Cambridge. This detailed study area was chosen as a result of the susceptibility of underlying stratigraphy and the dense coverage of available boring data. The stratigraphy includes former tidal marsh deposits of Holocene sand and silty sand along the margins of the river overlain by fill placed during the late 1800s and early 1900s. The detailed study region was used with geostatistical analysis to evaluate the variability of susceptible soils given a dense coverage of subsurface data.

The data from the test borings are entered into an electronic database (Microsoft Access) in order to facilitate relational database management and the flexibility of data input. In addition, the database structure easily allows for importing and exporting data using queries and direct links to other programs. The database is set up to store both general and geologic information gathered from the explorations such as the following: project information, date of boring, depth of boring, drilling company, engineering company, depths and descriptions of geologic units and samples, Standard Penetration Test (SPT) N-values, depth to groundwater, and x-y coordinate values. The relevant information required for liquefaction analysis is queried from the database and exported to a Liquefaction Module created in Excel which calculates the PGA trigger level that would induce liquefaction at each data point (discussed below). The calculated trigger levels are then imported into the database and subsequently queried and exported to a Geographic Information System (GIS; ArcView 8.2) for analysis and mapping. The GIS software is also used to analyze and map other relevant soil properties such as thickness and elevation of stratigraphic units as well as N-values.

Artificial Fill in Boston

As a result of the extensive history of filling in Boston, over one third of the surface area of Boston and Cambridge consists of artificial fill. Areas containing loose, granular, and saturated fill may be potentially liquefiable. Low-lying areas of Boston were filled beginning in the late 18th century as Boston outgrew the limited area of the original peninsula (Figure 1, Aldrich, 1970). Between 1856 and 1890, the Back Bay was filled between Charles Street and Fenway. The fill materials primarily consisted of sand and gravel from hills in Boston; sand and gravel brought by railroad from quarries outside of the city; and silts and clays dredged from the Charles River. On the Cambridge side of the Charles River, tidal marshes were filled in and the area was developed following the completion of a granite seawall in 1890 (Woodhouse, 1991). The bottom part of the fill in this area 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, 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. As a result of the granular nature of the fill placed in the Back Bay, we suspect that the fills in this region will be more susceptible to liquefaction than the more cohesive and fine-grained fills in Cambridge.

Properties of the artificially placed fill layer vary greatly on both the Cambridge and Back Bay sides of the Charles River. In general, the non-engineered 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, 1991). This variability of the fill has been confirmed in the boring logs collected and entered into our subsurface database.

Surficial Geologic Mapping

Mapping of surficial geologic deposits is currently being performed for this project. The mapping will allow for the delineation of units with similar geologic and geotechnical properties, which will provide a means for extending our analyses of liquefaction susceptibility from areas of well constrained subsurface data into areas where reliable borehole data is not available. Geologic units are mapped based on the depositional environment and age of the deposit. This information is useful in estimating characteristics of the units, including grain-size distribution and sorting, density, water condition, and degree of compaction in areas that lack subsurface data.

The surficial geology of the Boston area is dominated by deposits resulting from the extensive and repeated glaciation of the area throughout the Pleistocene. Glacial withdrawal in 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 resulted in complex distribution of estuarine and tidal marsh sediments. In addition, the Charles River deposited a sequence of fluvial sands and overbank silt deposits which line the margins of the river channel. Local beach deposits and tidal estuary deposits developed along active coastal areas and sheltered marshes, respectively.

We have produced a preliminary surficial geologic map of the Boston South Quadrangle. The surficial geologic map of the Boston South Quadrangle shows the areal distribution and composition of young, unconsolidated sediments. The map was based largely on previously published surficial geology maps, including Kaye (1976, 1982), Barosh et al. (1989), and Woodhouse (1991). Mapping is in progress for the remaining quadrangles in the study area, and refinement of the Boston South map continues with the continued collection of additional boring data. In our mapping, we have divided the surficial deposits into units representing both the characteristics and the origin of the deposits. Mapped geologic units include glacial till, glacial outwash and drift deposits, beach deposits, marsh and estuary deposits, and artificial fill. Regions of bedrock exposure and thin, discontinuous soil cover are also mapped. In general, the most extensive units in the Boston South quadrangle are the glacial outwash and the glacial till. The till lies directly on the bedrock surface and where present ranges in thickness from several meters to over 50 meters (Woodhouse et al., 1991). Till is exposed in drumlins which occur throughout the area as round to elliptical hills and highlands. The till is composed of poorly sorted sand, gravel, and cobbles in a clay matrix, and is in general well consolidated and very dense. The till unit represents the material carried and dropped during the two major glacial advances to occur in the area. The outwash deposits are stratified sands and gravels that vary in both density and consolidation. Thickness of outwash deposits can reach several meters. These sediments were deposited by stream outflows from the glacial front during glacial retreat.

A large portion of the downtown Boston area, including the waterfront areas, Back Bay, and Cambridge waterfront areas, are underlain by non-engineered artificial fill. These areas were originally low-lying tidal marshes, estuaries, and floodplains adjacent to the Boston Harbor and the Charles River. The character of the fill is discussed briefly above.

Groundwater Level

Since saturation is a requirement for liquefaction, groundwater levels are an important element of the hazard assessment. Since one potentially susceptible layer is surficial fill, the depth to groundwater will significantly impact the liquefaction hazard. When available, groundwater levels from observation wells and boring logs are entered into the database. From these data a general map of the groundwater condition of the study area will be derived. Because of potentially large seasonal and annual variability in the water table, we will attempt to estimate and use the historic high groundwater level in our assessment of liquefaction susceptibility.

Liquefaction Susceptibility

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.

The evaluation of liquefaction susceptibility is currently underway in this study, therefore only preliminary results exist. Zones corresponding to areas of very low to very high susceptibility have been defined based on a liquefaction triggering threshold analysis using SPT data in areas with borehole data, and with a criteria matrix based on the deposit s age, texture, and groundwater condition for areas lacking borehole data. Figure 2 shows the decision tree analysis for determining liquefaction susceptibility ratings.

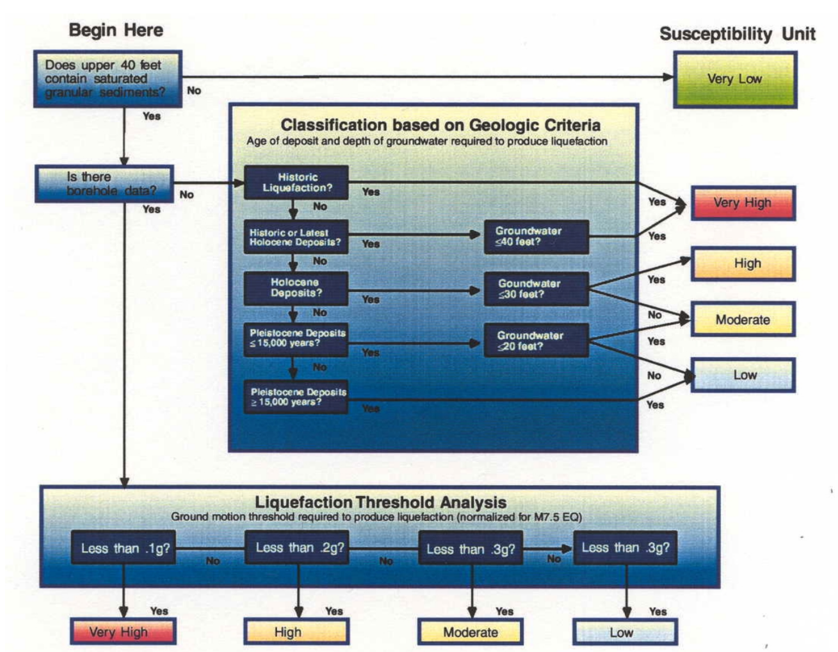

Figure 2 — Decision Tree Analysis for Liquefaction Susceptibility

When boring information is available, liquefaction susceptibility is 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 simplified method following 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, moisture content, soil type, and sample depth. CRR values were then compared to calculated shear stresses generated by the estimated ground motions, expressed in terms of cyclic stress ratio (CSR). The factor of safety (FS) relative to liquefaction is: FS = CRR/CSR. Generally, an FS of 1.0 or less, where CSR equals or exceeds CRR, indicates the presence of potentially liquefiable soil. Appropriate correction factors for SPT values were applied according to the values suggested in Youd et al. (2001). In order to create liquefaction hazard maps which summarize the peak ground acceleration (a_{max}) that will trigger liquefaction at a given location, we set the FS to 1 and inversely solved for the trigger value ($a_{max,\ trigger}$). This trigger value can then be summarized as very high, high, moderate, or low susceptibility as shown on Figure 2.

Our preliminary results from a densely sampled area north of the Charles River, as well as nearly 100 borings from the Back Bay and other areas of the Boston waterfront, indicate that the fill units are highly heterogeneous, with liquefaction triggering values ranging from less than 0.1g to more than 0.3g. The majority of the samples show relatively low or very low susceptibility (triggering values above 0.2g). However, in both the Back Bay and the Cambridge waterfront, the results indicate that a significant portion of the fill may trigger at ground motions less than 0.2g, and in some cases less than 0.1g. In addition, several samples taken from within the alluvial and estuarine deposits which underlie the artificial fill show low triggering levels as well. We are actively investigating the patterns and distribution of these areas of moderate and high susceptibility in both the artificial fill and in the natural sediments, and are collecting additional data from these units.

It should be noted that data collection from these areas is ongoing and these data will require further examination and review before final assessment of susceptibility as a whole can be made.

Spatial Statistics

We have focused on a densely sampled area along the Charles River to study the uncertainty in the subsurface data. This area is located in the Charles River alluvial fan and was extensively filled beginning in the 18th century; therefore, it represents a region with susceptible soils for liquefaction.

Geostatistical analyses were performed to explore the variability of adjusted SPT blow count $(N_1)_{60}$ values as well as liquefaction hazard predictions in the fill and natural sand deposits in the detailed study region shown in Figure 1. Initially, histograms were created to explore the distribution and statistics of the $(N_1)_{60}$ values. $(N_1)_{60}$ values for the fill layer range from 1 to 137 with an average of 24.2. $(N_1)_{60}$ values for the natural sand deposits range from 1 to 77 with an average of 20.9. The distribution of the fill $(N_1)_{60}$ values has a longer tail indicating more high-end outliers in the values than that observed in the natural sand values. The standard deviation for the $(N_1)_{60}$ values is 12.6 in the natural sand and 20.0 in the fill also indicating a smaller spread in the data for the natural deposits than the fill. Each of these observations is consistent with our understanding of the depositional environments and how deposition affects spatial variability of subsurface conditions. Therefore, density in the fill is expected to be more highly variable and difficult to predict than for the natural deposits.

In order to expressly look at the spatial correlation and variability in the $(N_1)_{60}$ values, experimental semivariograms were estimated. A semivariogram is a plot of the variance (one-half the mean squared difference) of paired sample measurements as a function of distance between the data points. The semivariograms of the average $(N_1)_{60}$ values for the fill and natural sand deposits were estimated. As expected the $(N_1)_{60}$ values for the natural sand deposits have less variability than the fill layer. The range for $(N_1)_{60}$ for the natural sands is near 500 ft, indicating that soil density can be extrapolated over distances within 500 ft of a boring. As shown on the histogram as well as the semivariogram, the fill layer is highly variable and has little correlation over small separation distances.

We are actively investigating spatial variability of both $(N_1)_{60}$ values and liquefaction trigger levels in the susceptible fill and natural sand deposits in order to better interpolate and extrapolate at unsampled points. Again, the data collection from these areas is ongoing and these data will require further examination and review before final assessment of spatial variability is made. Eventually, we hope to use geostatistical methods to help interpolate the hazard (in terms of liquefaction trigger values) at unsampled points.

References

Aldrich, H. P. Jr. (1970). Back Bay Boston, Part I, *Journal of the Boston Society of Civil Engineers*, Vol. 57, No. 1.

Hitchcock, C., Loyd, R., Haydon, W. (1999). Mapping Liquefaction Hazards in Simi Valley, Ventura, County, California, *Environmental & Engineering Geoscience*, Vol. V, No. 4.

Horn, H. M. and Lambe, T. W. (1964). Settlement of Buildings on the MIT Campus , *Department of Civil Engineering, Massachusetts Institute of Technology*.

Kaye, C. A. (1976). Outline of the Pleistocene Geology of the Boston Basin. *Geology of Southeastern New England* ed. B. Cameron. Science Press, Princetown, New Jersey, 46-63.

Kaye, C. A. (1982). Bedrock and Quaternary Geology of the Boston area, Massachusetts. *Geological Society of America: Reviews in Engineering Geology V*, 25-40.

Woodhouse, D., et al. (1991). Geology of Boston, Massachusetts, USA, *Bulletin - Association of Engineering Geologists*, Vol. 28, 375-512.

Youd, T. L. et al. (2001). Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils, *Journal of Geotechnical and Geoenvironmental Engineering*, October 2001.

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Non-technical summary:

This project is a two-year detailed study to characterize and map the potentially liquefiable deposits in Boston, Massachusetts including downtown Boston 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 is underlain by unconsolidated, granular Holocene alluvial deposits and extensive regions of artificial fill that, when saturated, are susceptible to liquefaction during seismic loading. Accurate, detailed maps of liquefaction susceptibility will allow communities to better plan and mitigate the effects of liquefaction on the built environment.

Reports Published:

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.

An abstract has been submitted to 2003 12th PanAmerican Conference on Soil Mechanics and Geotechnical Engineering and 39th U.S. Rock Mechanics Symposium at MIT. We will be submitting a paper for this conference and making a presentation in July 2003.

The subsurface data collected over the course of these investigations are not currently available but will be made available to the public at the completion of the project.