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THREE DIMENSIONAL LIQUEFACTION HAZARD ANALYSIS

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SUMMARY

In this study we use three-dimensional geostatistical interpolation techniques to predict the lateral extent of liquefiable soil for the East Cove and South Boston fill regions of Boston, Massachusetts. Extensive areas of downtown Boston are built on filled land. Filling operations have added approximately 5,250 acres of land to the Boston area over the last two centuries. Thousands of soil borings were advanced through this fill during the geotechnical investigations for the Central Artery Tunnel Project. In this study, we use the data obtained in the East Cove and South Boston fill regions to characterize the liquefaction hazard for the two regions. In order to understand the spatial extent of liquefiable soils, we quantify the spatial variability of the corrected blow counts [$(N_1)_{60}$]. We calculate the trigger acceleration for a factor of safety of 1.2 for 2247 soil samples. Because the corrected blow counts are highly variable, we assign indicator values to the calculated trigger accelerations and build a probabilistic three-dimensional model of the volume of theoretically liquefiable soil in each region using geostatistical interpolation. We quantify the confidence of the models and conclude with an analysis of the liquefaction hazard of the East Cove and South Boston fill regions.

Using this method we predict that a continuous plume of liquefiable soil exists in the South Boston fill region. At a probability of liquefaction equal to 0.7, this plume is approximately 8 to 30 feet thick, 1500 feet long, and 300 feet wide. We do not predict that the East Cove fill region has continuous, laterally extensive volumes of liquefiable soil for any probability of liquefaction greater than 0.3.

INTRODUCTION

Artificial fill underlies much of the Greater Boston area. A majority of this fill is granular and cohesionless. Granular, cohesionless soils are often susceptible to liquefaction during a seismic event. Ground failures associated with liquefaction can cause significant structural and lifeline damage in urbanized areas. In addition, four major earthquakes and several smaller seismic events have occurred in the vicinity of Boston since 1638. Given the physical presence of liquefiable sediments and the historic record of seismic activity, liquefaction induced ground failure in the Boston area is probable during a future earthquake.

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Typically, liquefaction hazard is presented as a two-dimensional phenomenon using flat maps (Lloyd, et al. [1], Broughton, et al. [2].) Liquefaction, however, occurs in three dimensions. Other researchers have shown that the occurrence of liquefaction-induced ground failures depends on the presence of a laterally extensive layer of liquefiable material (Youd, et al, [3], Ishihara [4].) The goal of this study is to use three-dimensional geostatistical interpolation to predict the extent of liquefiable soil for specific artificial fill regions in Boston, Massachusetts. The secondary goal of this study is to begin to determine the volume of theoretically liquefiable soil that is necessary to cause a ground surface disruption. This study is part of a larger project to further investigate the liquefaction hazard in Boston (Dawson [5], Baise, et al [6].)

Using the Kriging method, a geostatistical interpolation algorithm, we build volumetric models of the liquefaction potential of each fill region and quantify the spatial variability of the data used to build the model. To predict values at unsampled locations, we first determine the relationship between the difference in known sample values and the distance between the samples. This relationship is the semivariogram relationship. Typically, the variance between samples increases with increased distance. Using the semivariogram relationship, we assign weighting factors to samples surrounding each prediction point such that the sum of the weights used equals 1.0. Close samples are weighted higher than far samples according to the semivariogram relationship. The value at the unknown location is the sum of the weighted adjacent sample values. Since standard deviation is directly related to variance and since confidence is directly related to standard deviation, we are able to quantify the confidence of our interpolated models. (Clark [7], Houlding [8], Houding [9])

Traditional semivariograms, used to describe the spatial variation of two-dimensional data sets, are two-dimensional plots of semivariance versus distance. Since we utilized three-dimensional geostatistical interpolation, our semivariograms are three-dimensional plots of vector distance versus semivariance (Ctech [10].) The intent of using three-dimensional geostatistical interpolation was to build statistically defensible models of the volume of potentially liquefiable soil in the fill regions of Boston. Without three-dimensional interpolation, we would not be able to adequately characterize the lateral extent of potentially liquefiable plumes of soil or calculate the volumes of these plumes.

In this paper, we present a qualitative and quantitative analysis of two fill regions; East Cove and South Boston. The qualitative analysis consists of a review of the fill history of each region (Seasholes [11].) The quantitative analysis consists of a comprehensive three-dimensional analysis of the liquefaction hazard of each region using soil sample data.

The soil boring data used in this study were collected during the construction of the Central Artery Tunnel Project, (CA/T [12].) The soil boring database consists of boring logs for 41,374 soil samples obtained from 1,942 borings. The soil borings are located along the alignment of the Central Artery Tunnel and are spaced approximately 75 to 120 feet apart. 87 borings (382 soil samples) are located in the East Cove fill region. 254 borings (1,422 soil samples) are located in the South Boston fill region. To analyze the liquefaction hazard of the fill regions, we calculated the acceleration value necessary to cause liquefaction at a factor of safety of 1.2 for each sample using the Simplified Seed & Idriss Method (Youd, et al. [13].) We then studied the spatial correlation of the corrected blow counts, $[(N_1)_{60}]$. Finally, we assigned indicator values to each soil sample. We chose to use indicator values because the scatter in the $(N_1)_{60}$ values and acceleration trigger values was extensive. Samples with calculated trigger acceleration values below 0.12, the design earthquake acceleration value for Boston, received an indicator value of 1.0. Samples with calculated trigger acceleration values above 0.12 received an indicator value of 0.0. Using indicator kriging, we developed a three-dimensional model of the probability of liquefaction for each fill region. Finally we studied the predicted volume and lateral extent of theoretically liquefiable soil for each fill region. See Dawson [5] for the development of the methodology used for this study.

FILL HISTORY OF EAST COVE FILL REGION

East Cove, known today for Faneuil Hall, Quincy Market, Rowes Wharf, and the Harbor Towers was once the home of Boston's earliest settlers. The filling of East Cove added nearly 110 acres of land to the original Boston peninsula (Ty [14].) Boston's founders inhabited the shore of East Cove in 1630. Soon after their arrival, the settlers constructed wharves. By 1711, these early, shallow-water wharves were obsolete. To support the growing maritime economy, Bostonians built Long Wharf in 1711, Figure 1. Long Wharf was the first deep-water wharf and remains today. [Seasholes [11]

Long Wharf extended from the mainland to the arc of the Barricado, a defensive barricade built in 1708. The wharf was built from wood cribbing, gravel, debris, and possibly ashes from the Fire of 1711. By 1844, landowners along East Cove had filled the land between the shallow-water wood and earth wharves with ash, deceased animals, and trash. High concentrations of smoking pipes and other artifacts indicate that the areas between the early wharves were "filled rapidly in the early 18th century, probably with whole cartloads of refuse that were simply dumped" (Seasholes [11].)

By 1750, Bostonians had built several deep-water wharves including India Wharf. As new, longer wharves were added, the land between the shallow-water wharves was filled. Many of the new wharves were constructed with stone sea walls built on a foundation of wood piles and filled with any available material including "good upland fill" and "sod and marsh mud" (Seasholes [11].) Buildings that were built on these wharves were often supported on wood piles since material used to fill the wharves could not support building loads. (Seasholes [11])

From 1860 to 1870, Bostonians built Atlantic Avenue, Figure 2. The construction of Atlantic Avenue required extensive filling of the area between existing wharves. Material for this large scale filling effort was imported by railcar from Fort Hill, one of the original hills on the Boston peninsula. Fort Hill consisted mainly of silty sand with some clay and gravel. (Seasholes [11])

From the fill history of East Cove, we conclude that landfill is highly heterogeneous. 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.

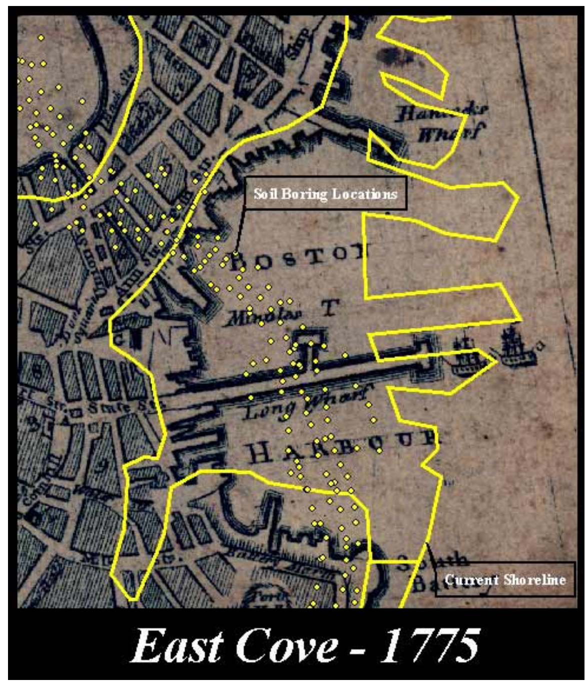

Figure 1. Historic Map of East Cove from 1775 with Soil Boring Locations and the Approximate Outline of the Current Shoreline (Norman [15])

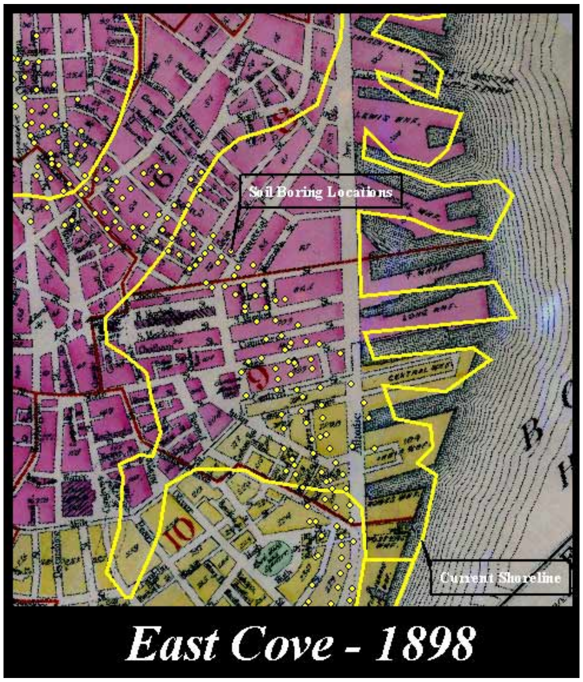

Figure 2. Historic Map of East Cove from 1898 with Soil Boring Locations and Approximate Outline of Current Shoreline (Index Map, [16])

THREE-DIMENSIONAL MODEL FOR EAST COVE FILL REGION

382 soil samples from 87 borings performed during the construction of the Central Artery Tunnel Project are located in the East Cove fill region. In order to confirm the expected heterogeneity of the region, we determined the spatial variability of the corrected blow count values, [$(N_1)_{60}$]. The secondary intent of studying the spatial variability of the $(N_1)_{60}$ values was to determine the semivariogram relationship for the study data set.

From the three-dimensional semivariogram of the $(N_1)_{60}$ values we determined that the range of the semivariogram is 918 feet and that the sill of the semivariogram is 4,371, Figure 3. Out of all the Boston fill regions studied, East Cove has the highest sill value and the second lowest range. The sill value is the highest average semivariance in the data set. The range is the distance over which the data are correlated. Beyond 918 feet, the $(N_1)_{60}$ values are no longer related.

The $(N_1)_{60}$ values vary tremendously over small distances, Figure 4. From the semivariogram we can see that large pair differences dominate the semivariogram. These large pair differences are plotted above the semivariogram surface. The semivariogram surface is fit to the data using a least squares regression analysis. The total length of lines above the surface equals the total length of lines below the surface. Each line is plotted from the vector distance between the data pair. The length of the line from the point of origin equals the semivariance of the data pair. The surface is then fit between the lines so that the total length of the lines above the surface equals the total length of the lines below the surface.

Using geostatistics, we also examined the confidence of the interpolated model of $(N_1)_{60}$ values. Since the sill is high and the range is low, we cannot interpolate $(N_1)_{60}$ values over large distances at high confidence levels. We cannot interpolate far from our sample values even at a 50 percent confidence level, Figure 5. The volume shown in Figure 5 is the volume of liquefiable soil that we predict exists with at least 50% confidence. This volume is small and the potential error is high. The spatial variability of these data is so high that we cannot predict $(N_1)_{60}$ values at unknown locations within the extent of our data with any level of confidence greater than 35 percent, Figure 6.

From Figures 4, 5, and 6, we conclude that the $(N_1)_{60}$ values for the East Cove fill region are highly spatially variable and consequently the fill is highly heterogeneous. Although we could have predicted this high variability based on the fill history of the region, it is essential to quantify the variability in order to interpret the three-dimensional liquefaction hazard model.

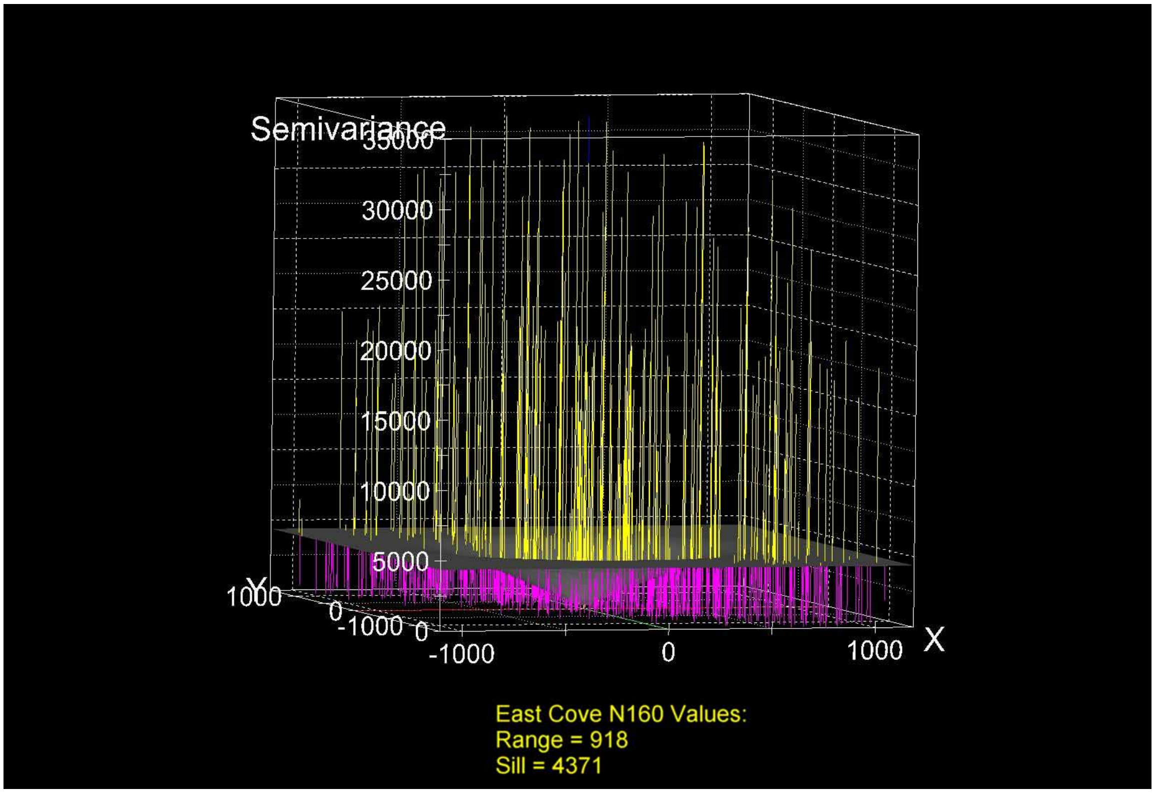

Figure 3. 3D Semivariogram of $(N_1)_{60}$ Values for East Cove

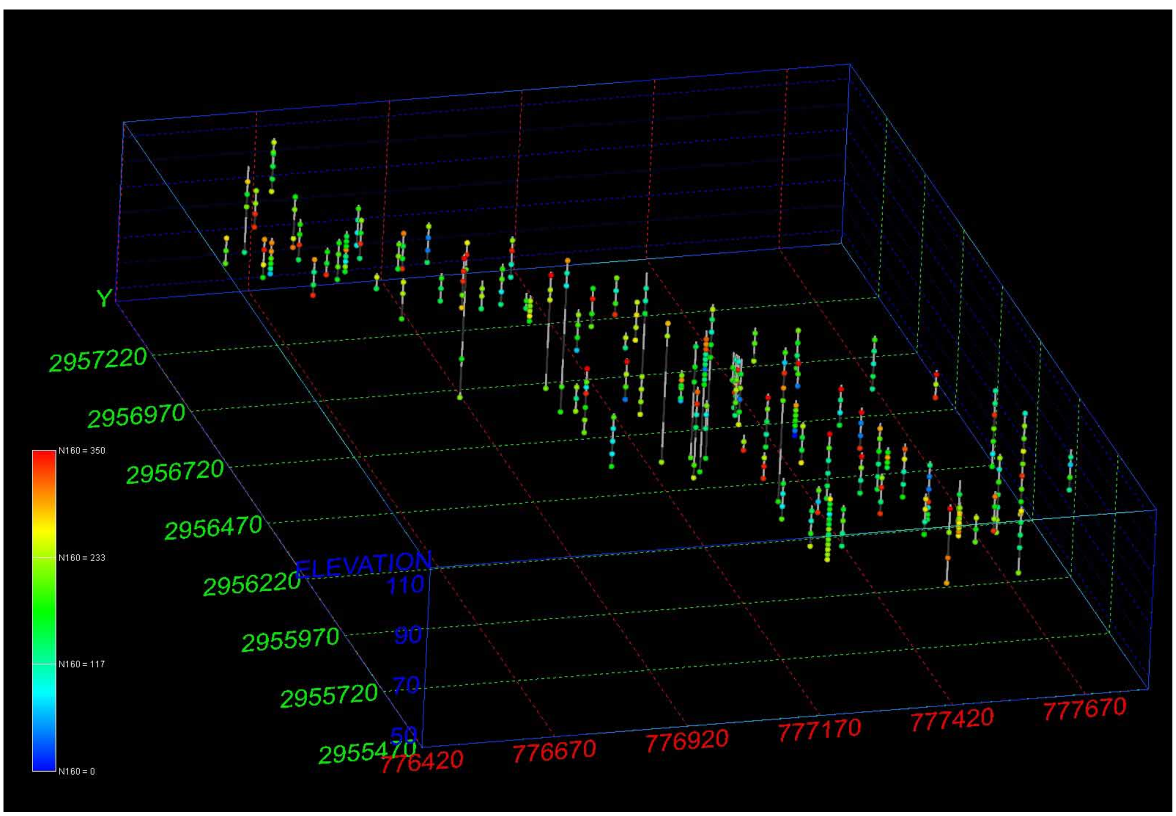

Figure 4. **$(N_1)_{60}$ Values for Soil Samples in East Cove. Sphere Color Corresponds to $(N_1)_{60}$ Value**

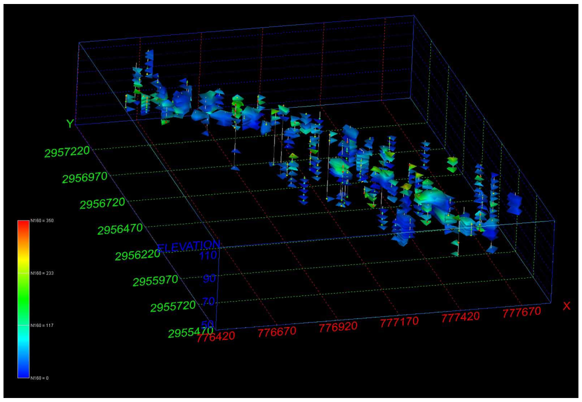

Figure 5. Model of Predicted $(N_1)_{60}$ Values for 50% Confidence for East Cove

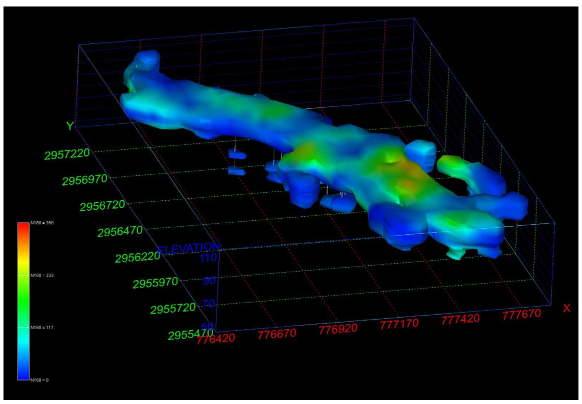

Figure 6. Model of Predicted $(N_1)_{60}$ Values for 35% Confidence for East Cove

The three-dimensional semivariogram of the liquefaction indicator values has the same range as the semivariogram for the $(N_1)_{60}$ values, Figure 7. The sill of the semivariogram model equals 0.05. The sill is significantly lower because the range of indicator values is from 0 to 1. Again the semivariogram is dominated by large pair differences. Since the range of the semivariogram for the liquefaction indicator values is relatively low and the sill is high, we anticipate that we will not predict large volumes of liquefiable soil for high probability values. The volumes of liquefiable soil will be associated with individual samples rather than with larger regions.

For a probability of liquefaction equal to 0.7, the predicted volume of liquefiable soil is associated with individual sample values, Figure 8. For a probability of liquefaction equal to 0.7, we expect liquefaction of small, isolated volumes of soil.

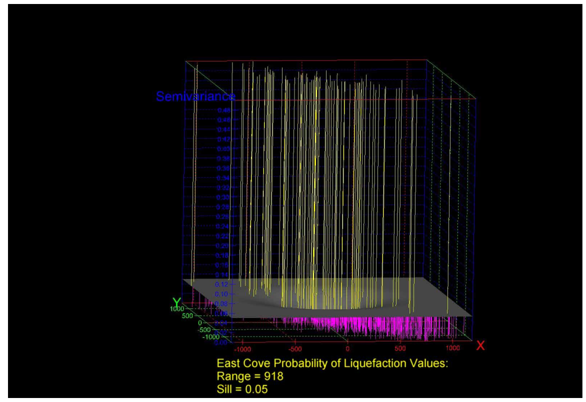

Figure 7. 3D Semivariogram of Indicator Values for East Cove

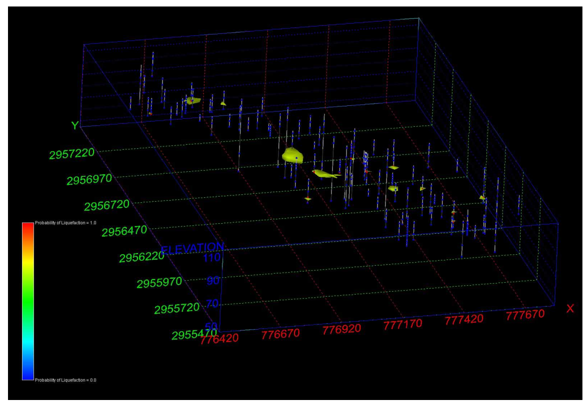

Figure 8. Model of Liquefiable Volume of Soil for a Probability of Liquefaction Equal to 0.7 in East Cove

At a probability of liquefaction equal to 0.3, we predict a sizable plume of liquefiable soil on the northwest side of East Cove, Figure 10. We use the term plume to describe a continuous volume of soil that meets specific criteria. In this case, the plume is the volume of soil that is theoretically liquefiable at a probability of liquefaction equal to 0.3. This plume is approximately 375 feet long, 375 feet wide, and 25 feet thick. The location of this plume coincides with the location of the fill placed between some of Boston's earliest shallow-water wharves. Records indicate that this area of East Cove was most likely filled with loosely placed refuse and gravel.

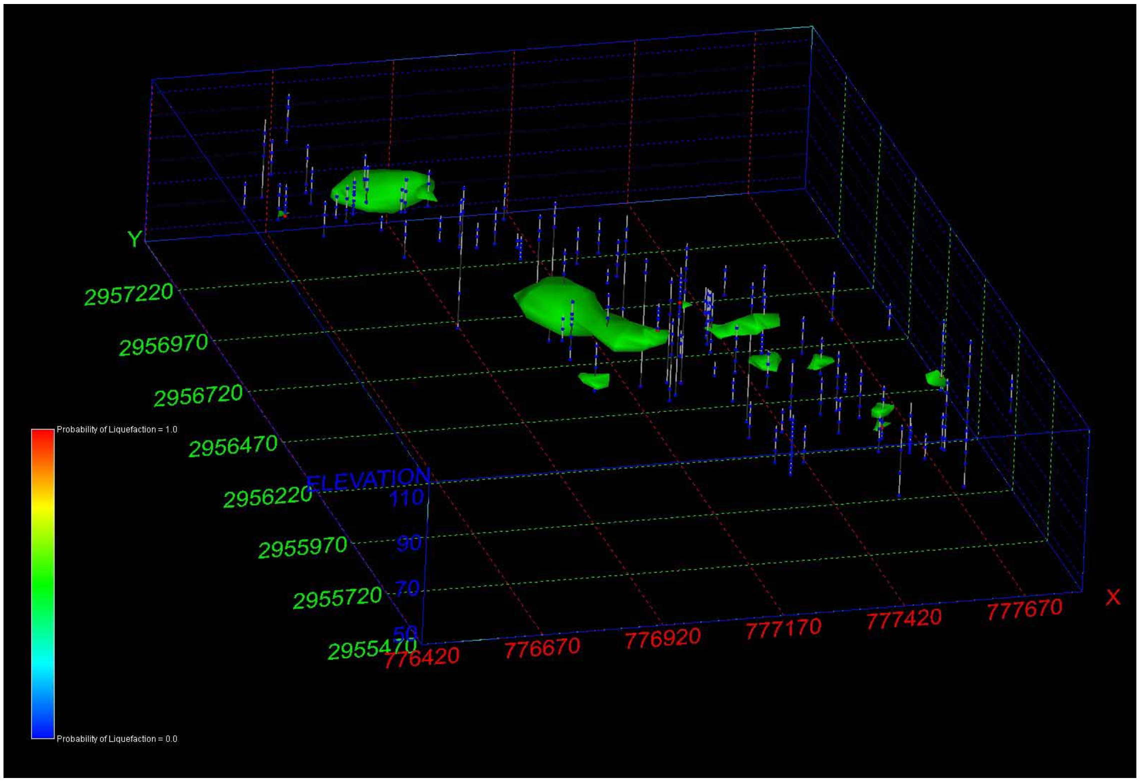

Figure 9. Model of Liquefiable Volume of Soil for a Probability of Liquefaction Equal to 0.5 in East Cove

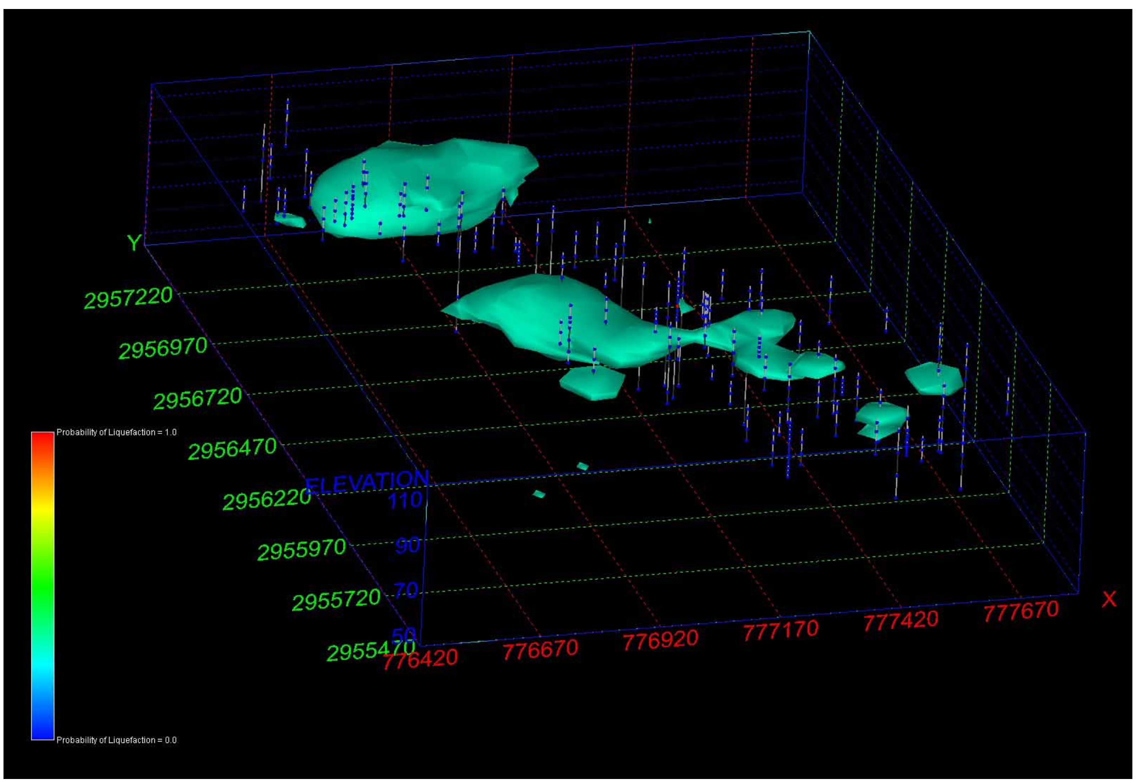

Figure 10. Model of Liquefiable Volume of Soil for a Probability of Liquefaction Equal to 0.3 in East Cove

A second sizable plume of liquefiable soil also develops at a probability of liquefaction equal to 0.3. The plume is approximately 625 feet long, 185 feet wide, and 5 to 30 feet thick. The location of this plume coincides with the location of the original Long Wharf, the first deep water wharf constructed in Boston. The exact nature of the material used to fill Long Wharf is not known. However, some reports indicate that Long Wharf may have been filled with gravel as well as ash and debris from the Fire of 1711.

From the three-dimensional liquefaction analysis of East Cove we can make several conclusions. First, the fill layer in East Cove is highly variable. Second, the overall number of liquefiable soil samples within east cove is low. Only 17 out of 406 samples (4.2%) that were analyzed were classified as liquefiable. Given the high variability of soil conditions within East Cove and the low number of liquefiable soil samples, we did not expect to predict significant connecting volumes of liquefiable soil. Our models show that even at very low probabilities of liquefaction, we do not predict large volumes of liquefiable soil. Furthermore, since these volumes are mostly isolated, we do not predict that significant ground deformations due to liquefaction will occur in East Cove during a seismic event equal to the design earthquake defined in the Massachusetts state building code.

FILL HISTORY OF SOUTH BOSTON FILL REGION

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, Figure 11. In the early 1800s, filling was completed to create new land for industry. The majority of the fill used at this time was excavated from the hills in the original South Boston. (Seasholes [11])

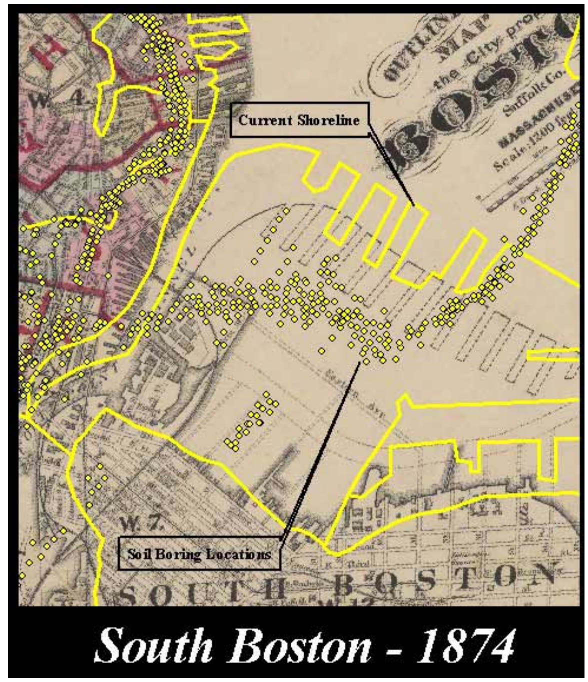

Figure 11. Historic Map of South Boston from 1874 with Soil Boring Locations and Approximate Outline of Current Shoreline (Busch [17])

In the 1850s, the city of Boston moved all public asylums to South Boston including the House of Industry, the House of Corrections, and the Institution for Reformation of Juvenile Defenders (Seasholes, [11].) To create land for these institutions, the city extended Broadway Street, cutting down the hills of South Boston and dumping the fill in the flats. In 1863, the Boston, Hartford, & Erie Railroad constructed a trestle Bridge over the South Boston Flats and the Fort Point Channel to connect to the mainland. At this same time, the city realized that Boston's shipping industry had declined severely. The shipping lanes in and out of the harbor had narrowed tremendously. (Seasholes [11])

In an effort to revive the maritime economy, the state and city asked the U.S. government for a formal harbor survey. In 1863, the U.S. Commissioners on Boston Harbor issued a map that showed a massive sea wall extending around the South Boston flats. The intent of the wall was to increase the scour in the main shipping channel so that the channel would stay open without dredging. (Seasholes [11])

Filling began in 1869 and was completed by the Boston, Hartford & Erie Railroad and the Boston & Albany Railroad using material that was dredged from outside the seawall. When the Boston, Hartford & Erie Railroad went out of business in 1870, the Boston Wharf Company foreclosed on the mortgage for the land that the railroad was to create. The Boston Wharf Company continued the filling operation using material imported from Fort Hill and debris from the fire of 1872. (Seasholes, [11])

In 1881, the city signed a contract with New England Dredging Company to fill the area south of Eastern Avenue. At the same time, the U.S. government and other private companies dredged the shipping channel in the harbor and dumped the dredged material in the South Boston flats. This dredged material consisted of “mostly sand with some stones and clay” (Seasholes, [11].) Ashes and household trash was also occasionally mixed with the dredged material. (Seasholes [11])

From 1892 to 1895 hydraulic dredges were used to fill a 70 acre parcel in South Boston. The use of the hydraulic dredge was revolutionary. The hydraulic dredge deposited material evenly, saving on the cost of grading the material. However, the deposited material was very loose and took years to consolidate. (Seasholes [11])

In 1897, Commonwealth Pier was constructed. The pier was intended to be a model pier for the rest of the South Boston development. In 1914, the largest drydock in the world was constructed on the South Boston waterfront. A year earlier, Fish Pier was built. Commonwealth Pier, Fish Pier, and the drydock were all filled with a mix of hydraulically placed material and scoop-dredged material. (Seasholes, [11])

In 1918, the federal government purchased a large portion of the remaining South Boston Flats, filled the area and used it as a shipping terminal during World War I. The remainder of South Boston was filled using hydraulic dredges between 1918 and 1934. (Seasholes, [11])

The majority of the fill in South Boston consists of fine silty sand with some clay. This mostly cohesionless fill was placed by hydraulic dredge and is expected to be loose. Because the fill is most likely loose, cohesionless, and saturated, we expect that it may be susceptible to liquefaction during a seismic event.

THREE-DIMENSIONAL MODEL FOR SOUTH BOSTON FILL REGION

Based on the fill history of South Boston, we anticipate that the fill layer will be more spatially coherent than the fill layer in East Cove. The analysis of the $(N_1)_{60}$ values confirms our hypothesis. The range of the semivariogram for $(N_1)_{60}$ values equals 3343 feet, Figure 12. The sill of the semivariogram for the $(N_1)_{60}$ values equals 897, Figure 12. The range is significantly higher and the sill is significantly lower than the range and sill for $(N_1)_{60}$ values in East Cove. The $(N_1)_{60}$ values in South Boston are far more spatially correlated than the $(N_1)_{60}$ values in East Cove. We anticipated this strong spatial correlation since the majority of the fill in South Boston was deposited by hydraulic dredge.

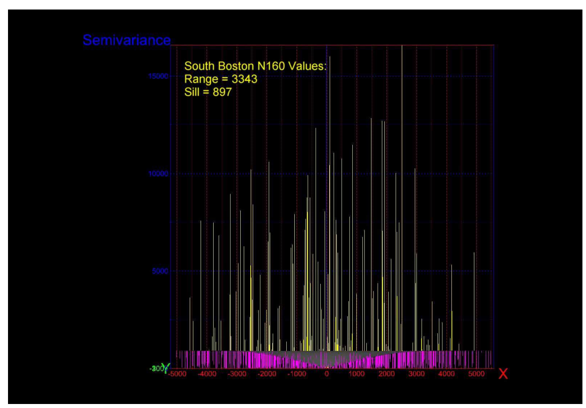

Figure 12. 3D Semivariogram of $(N_1)_{60}$ Values for South Boston

The confidence of the interpolated model of $(N_1)_{60}$ values is significantly higher than the confidence of the model of $(N_1)_{60}$ values for East Cove. At 80% confidence, the model of $(N_1)_{60}$ values is continuous within the data cluster, Figure 13. At 50% confidence, we are able to interpolate unknown values approximately 400 feet from our known data locations, Figure 14.

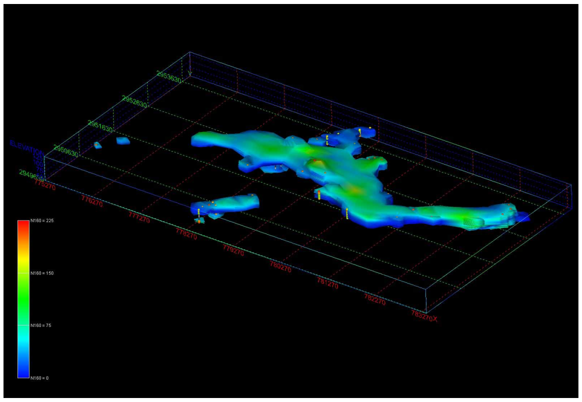

Figure 13. Model of Predicted $(N_1)_{60}$ Values for 80% Confidence for South Boston

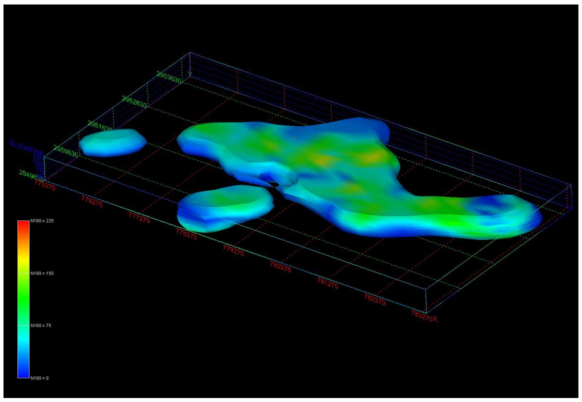

Figure 14. Model of Predicted $(N_1)_{60}$ Values for 50% Confidence for South Boston

The fill in South Boston appears more layered than the fill in East Cove, Figure 15. There are far fewer lenses and instances of extreme localized variation of $(N_1)_{60}$ values than there are in the East Cove fill region, Figure 15.

Based on the fill history of South Boston and an analysis of the $(N_1)_{60}$ values, we predict that the region may contain a significant volume of theoretically liquefiable soil. Fill records indicate that the fill consists of a silty fine sand and was placed by hydraulic dredge. The analysis of $(N_1)_{60}$ values revealed that the fill in South Boston is layered. Additionally, there is a relatively uniform layer of soil with low $(N_1)_{60}$ values. Given that the fill is saturated, loose, and mostly granular, we predict that a significant volume of soil may be liquefiable at a relatively high probability of liquefaction.

Using three-dimensional geostatistical interpolation, we predict a significant plume of liquefiable soil at a probability of liquefaction equal to 0.7, Figure 16. This plume is located on the eastern side of South Boston and corresponds to the location of the most recent filling. The material that was placed in this area typically consists of fine silty sand with some clay. The material was hydraulically dredged from Pleasure Bay in Marine Park. For a probability of liquefaction equal to 0.7, the plume of theoretically liquefiable soil is approximately 8 to 30 feet thick, 1500 feet long, and 300 feet wide. The top of the plume is located approximately 10 to 15 feet below ground surface.

At a probability of liquefaction equal to 0.5, this size of the main plume expands significantly, Figure 17. At this probability of liquefaction the plume is approximately 10 to 60 feet thick, 2,500 feet long, and 500 feet wide. The top of the plume is located approximately 8 to 10 feet below ground surface. At a probability of liquefaction equal to 0.5, a number of smaller plumes of theoretically liquefiable soil are present throughout South Boston. These smaller plumes are located at approximately the same depth as the main plume. At a probability of liquefaction equal to 0.3, the smaller plumes connect with the larger dominant plume of theoretically liquefiable soil, Figure 18. A fence diagram through the data in South Boston reveals a distinct layer of liquefiable soil, Figure 19.

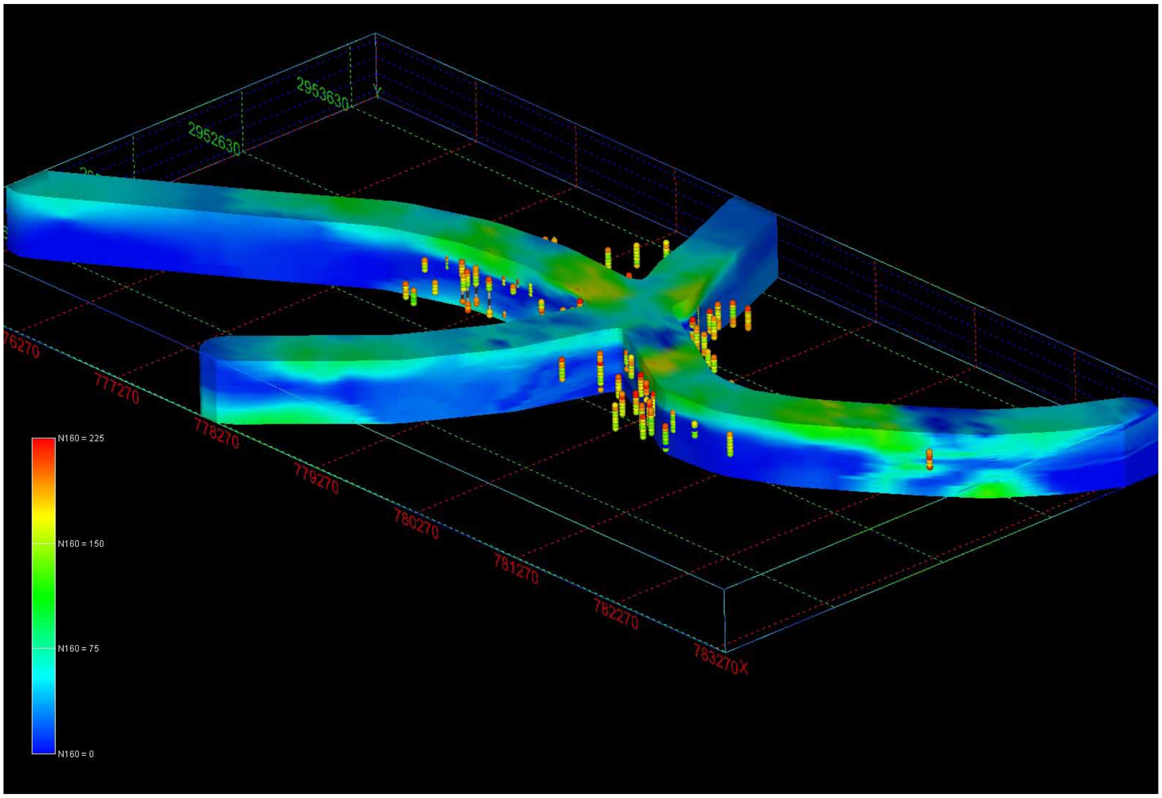

Figure 15. Slice Through Model of Predicted $(N_1)_{60}$ Values for South Boston

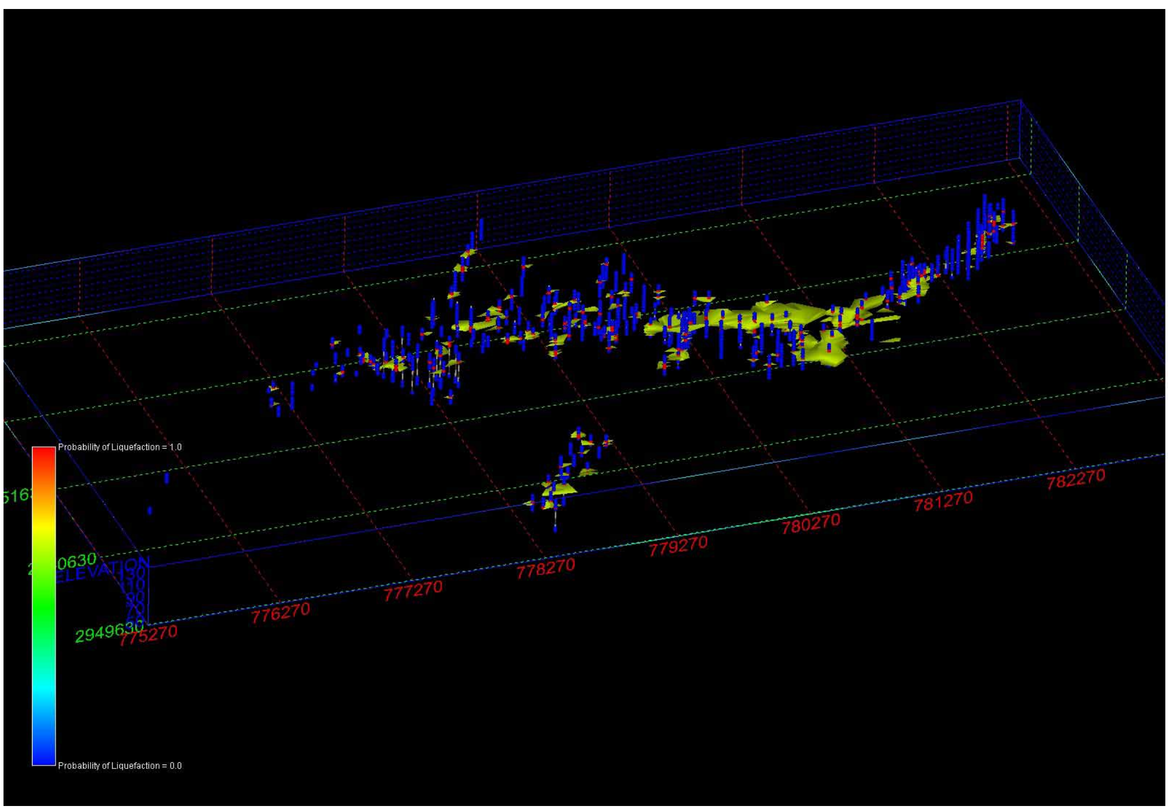

Figure 16. Model of Liquefiable Volume of Soil for a Probability of Liquefaction Equal to 0.7 in South Boston

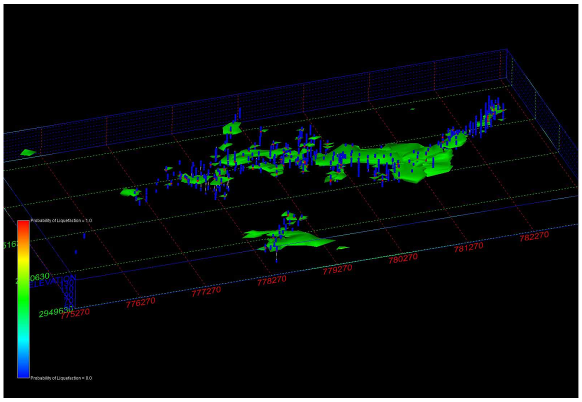

Figure 17. Model of Liquefiable Volume of Soil for a Probability of Liquefaction Equal to 0.5 in South Boston

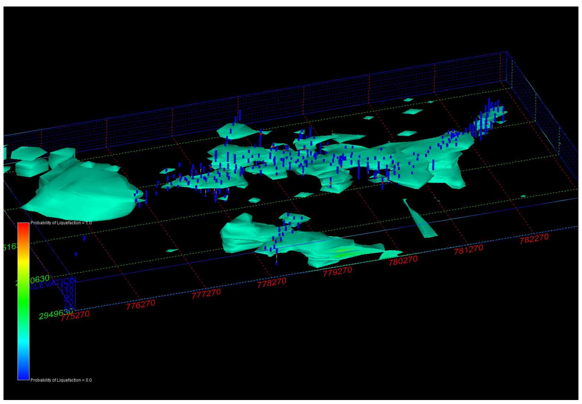

Figure 18. Model of Liquefiable Volume of Soil for a Probability of Liquefaction Equal to 0.3 in South Boston

From the three-dimensional liquefaction analysis of South Boston, we can make several conclusions. First, the $(N_1)_{60}$ values in the fill layer of South Boston correlate well spatially. The fill has distinct layers of relatively uniform density. There is also a laterally extensive layer of loose soil located approximately 12 to 15 feet below the ground surface. Approximately 16.9% of the soil samples from South Boston are theoretically liquefiable. The majority of these samples were taken from the layer of loose soil 12 to 15 feet below the ground surface.

At a probability of liquefaction equal to 0.5, we predict that a significant, laterally extensive volume of theoretically liquefiable soil exists near the eastern edge of South Boston. At this probability level, the liquefiable plume is 10 to 60 feet thick. This combination of liquefiable layer thickness and overlying non-liquefiable layer thickness plots above the bound for liquefaction induced ground damage proposed by Ishihara [4]. Based on the fill history and three-dimensional liquefaction hazard analysis, we conclude that significant ground deformations due to liquefaction may occur in South Boston during a seismic event equal to the design earthquake defined in the Massachusetts state building code.

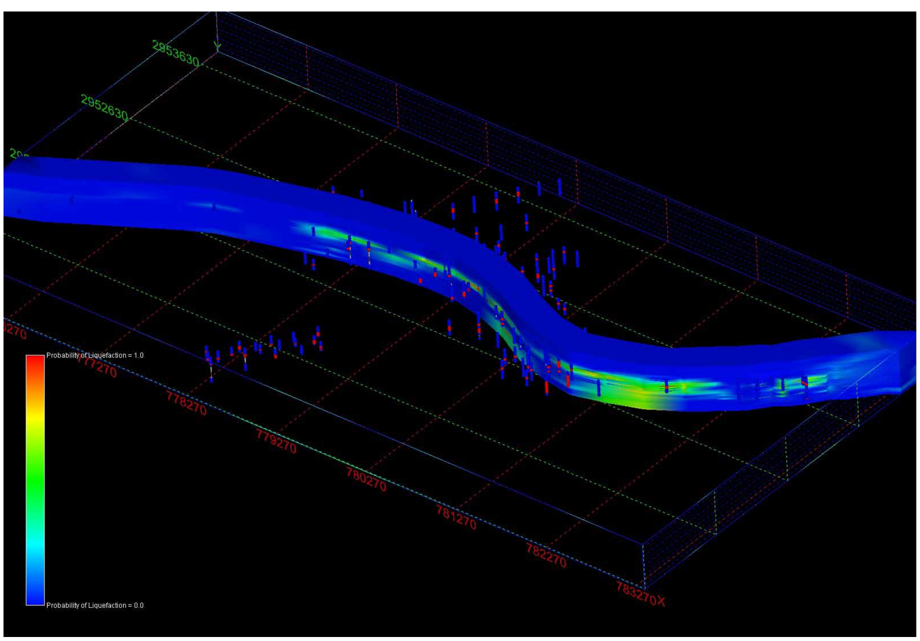

Figure 19. Slice Through Model of Liquefiable Volume of Soil for South Boston

CONCLUSION

One of the largest problems researchers encounter when studying liquefaction hazard is determining the spatial extent of a potentially liquefiable plume. One way to accurately characterize liquefaction hazard is to build three-dimensional models of liquefiable soil using geostatistical interpolation techniques.

Using three-dimensional liquefaction hazard analysis, we were able to visualize the potentially liquefiable soil in the fill regions of Boston, Massachusetts. Additionally, we were able to quantify the spatial variability of our data and examine the confidence of the resulting interpolated model of theoretically liquefiable soil. Ultimately, three-dimensional liquefaction hazard analysis could be used to determine the volume of theoretically liquefiable soil that is necessary to cause liquefaction-induced ground failure.

Based on our analysis we conclude that the lateral extent of the liquefiable plume for the East Cove fill region of Boston is relatively small even at low probabilities of liquefaction. Although 4.2% of the soil samples in East Cove are theoretically liquefiable, these samples are not clustered in any one area. East Cove does have lenses of potentially liquefiable soil. However, since lenses of liquefiable soil rarely cause large ground failures, we do not believe that the liquefaction hazard of the East Cove fill region is high.

In South Boston 16.9% of the study soil samples are theoretically liquefiable. These samples typically exist in a laterally extensive layer of potentially liquefiable soil located approximately 12 to 15 feet below the ground surface. 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 plume is approximately 8 to 30 feet thick, 1500 feet long, and 300 feet wide. Based on the criteria established by Ishihara [4], this liquefiable layer may cause a significant ground failure during a seismic event equal to or greater than the Massachusetts state building code design earthquake.

Three-dimensional liquefaction hazard analysis has proven to be an effective means of quantifying the lateral extent of liquefiable soil. Geostatistical modeling techniques further enhance the capabilities of three-dimensional analysis. Using three-dimensional geostatistical interpolation, researchers and engineers can quantify the spatial variability and confidence of any predictive model. Three-dimensional geostatistical interpolation offers tremendous potential for the geotechnical and specifically the earthquake engineering fields.

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