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EVALUATION OF SHAKE AND LIQUEFACTION DAMAGES DUE TO EARTHQUAKE SCENARIOS IN BOSTON, MASSACHUSETTS

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Abstract

Boston is one of the oldest cities in the United States with many 19th-century apartments and numerous architecturally and culturally significant historical buildings. The Boston area is known to have moderate seismicity, but the largest event in modern history was the 1755 Cape Ann earthquake. Given the immense growth and development in the last two centuries compounded with the practice of land making in the city, the recurrence of an event similar to the Cape Ann earthquake could have a significant impact in terms of damage and loss.

In this study, multiple earthquake scenarios are evaluated to provide a historical perspective of loss and also damage estimates of event scenarios that are consistent with the design hazard level in the Massachusetts Building Code. Out of these scenarios, plausible events are selected and a detailed shake and liquefaction study is performed. Our detailed analysis was made possible by developing high resolution shear-wave velocity, liquefaction susceptibility, and groundwater depth maps for Boston and leveraging AIR's existing US Earthquake model. The existing building inventory for Boston is modeled using AIR's high resolution building exposure database.

Our evaluation shows that while the 1755 Cape Ann earthquake would be devastating if it were to happen again today, a future event with a design code level recurrence and intensity could cause much more devastation and inflict tens of billions of dollars in economic losses. Building damage due to ground shaking could be significant but the damage due to liquefaction is much less severe than those observed in very susceptible areas. Construction practice, using timber piles rather than shallow foundations to support the buildings, is one of the main reasons that the threat of liquefaction is less severe to buildings. However, liquefaction damages to utilities, roads, and aging infrastructures could be significant, where the extent of damage could have a profound effect on the resiliency of the city after such an event.

Keywords: Scenario Study; Loss Estimation; Damage; Liquefaction, Resiliency

1. Introduction

Boston is one of the oldest cities in the United States with many 19th-century apartments and numerous architecturally and culturally significant historical buildings. Many of these buildings were made using unreinforced masonry construction which has been shown to be very susceptible to damage or collapse during past earthquakes.

The city has also grown significantly in the last 300 years. Numerous land reclamation projects have changed the landscape of the city. Originally, Boston was consisted of a small peninsula which was surrounded by tidal marshes and connected to the mainland by a relatively narrow land bridge at the time that first settlers arrived in this area in the mid-17th century. During the development of the Boston area, these tidal marshes have been filled with soil brought from surrounding areas or from dredging the harbor and waterways. Observations from previous earthquakes have demonstrated that reclaimed and filled areas such as these are more susceptible to both ground shaking due to site amplification and also liquefaction because of high groundwater levels and loose conditions of filled areas with no proper engineering compaction.

Boston is regarded as an area with moderate seismicity. One of the most severe earthquakes known to have occurred in the northeast was the Cape Ann earthquake of 1755, which struck the Boston, Massachusetts area. During that time, Boston was a small settlement, but reported damage from this event has allowed researchers to approximately locate the epicenter, estimate the magnitude, and better understand the seismicity of Northeast United States [1].

Several studies have been conducted to evaluate potential damage and losses due to possible earthquake scenarios in the Boston area. Most of these studies relied on HAZUS-MH (a damage and loss estimation software developed to estimate potential losses from natural disasters) or its predecessors. In a pilot study for National Institute of Building Sciences in 1997, EQE International estimated that the total loss due an event similar to the 1755 Cape Ann event would cause USD $1.9B in total loss in the city of Boston alone of which USD $1.1B would be direct losses from damage to buildings and contents [2]. Whitman reported a study as part of the HAZUS development which resulted in USD $1.14B of damage to buildings in the city of Boston using an inventory of buildings prepared as part of the HAZUS pilot study if the 1755 Cape Ann event reoccurred assuming uniform soil class D everywhere in the city [3]. In another study in 2003, HAZUS99 program was used to estimate the losses for large earthquakes in Suffolk County (including cities of Boston, Chelsea, Revere, and Winthrop) [4]. Using HAZUS-MH, in a study in 2008, it was estimated that if another 1755 Cape Ann earthquake were to occur today, it would result in approximately US $1.2B (1994 dollars) in total economic loss and 15 fatalities in Suffolk County [5].

In a study for the Federal Emergency Management Agency (FEMA), the New England Shake Map/HAZUS Working Group, estimated damages and losses for several earthquake scenarios in New England [6]. An event similar to the 1755 Cape Ann earthquake was estimated to cause total of USD $3.2B losses in Massachusetts, New Hampshire and Rhode Island, with only one fatality and 230 injuries. However, they mentioned that their estimate is low because of an underestimated number of URM buildings particularly in Boston. Additionally it was noted that the site class map used for the study did not account for fill and alluvial deposits in Boston. In another study using HAZUS-MH, it was estimated that the total damages for a magnitude 5.0 earthquake with an epicenter in downtown Boston would cause USD $3.4B in the city of Boston. This number includes building, content, and business interruption losses [7]. The estimated losses for an earthquake similar to the 1755 Cape Ann earthquake was USD $431M resulting from damage to buildings including USD $113M due to business interruptions, 5 fatalities and 139 injuries in the City of Boston alone [7].

As summarized here, a wide range of losses for different scenario studies are reported for plausible earthquakes in the Boston Area relying on the HAZUS framework and inventory for loss estimation. This study aims to conduct an independent assessment on the extent to which earthquake shaking and liquefaction are to be expected and the anticipated severity of damage and casualties if a plausible earthquake were to hit the Boston area. In this study, several earthquake scenarios are studied and loss and casualties are estimated using the Earthquake model developed by AIR Worldwide for the United States with improved inventory of buildings in

90-meter resolution in addition to an improved liquefaction module which has incorporated lessons learned from the Canterbury, New Zealand Earthquake Swarm in 2010 and 2011.

2. Earthquake Hazard in Boston

A large number of intraplate earthquakes have occurred in the Northeastern United States. They are rare compared to California or other areas of high seismicity but seismic events have been frequently observed, indicating that some crustal deformation is occurring. Most earthquakes in this region have small magnitudes but they usually felt in a bigger area.

One of the most severe earthquakes known to occur in the Northeast United States was the 1755 Cape Ann earthquake, which caused considerable damage in the Boston area and it was felt all the way to Halifax, Nova Scotia in the North, Lake Champlain in New York State and in Winyah, South Carolina [1]. The moment magnitude of that event is estimated to be between 5.6 and 6.6 [8]. Fig. 1 shows earthquakes with magnitude of 4 or higher in this area in the last 4 centuries.

The seismicity of the Northeastern United States is also impacted by the Charlevoix seismic zone in eastern Canada, located along the St. Lawrence River, about 400 kilometers north of Boston. The deaggregation of seismic hazard, which shows the range of Magnitude-Distance that could potentially affect a region, suggests that the expected hazard in Boston is derived from relatively low-magnitude events occurring close to Boston [12]. This has also been observed by others [9]. As shown in this figure, a wide range of Magnitude-Distance contributes in the hazard level in Boston, which is very different from deaggregation of hazard in California where well-studied faults dominate the hazard with a narrower range of Magnitude-Distance.

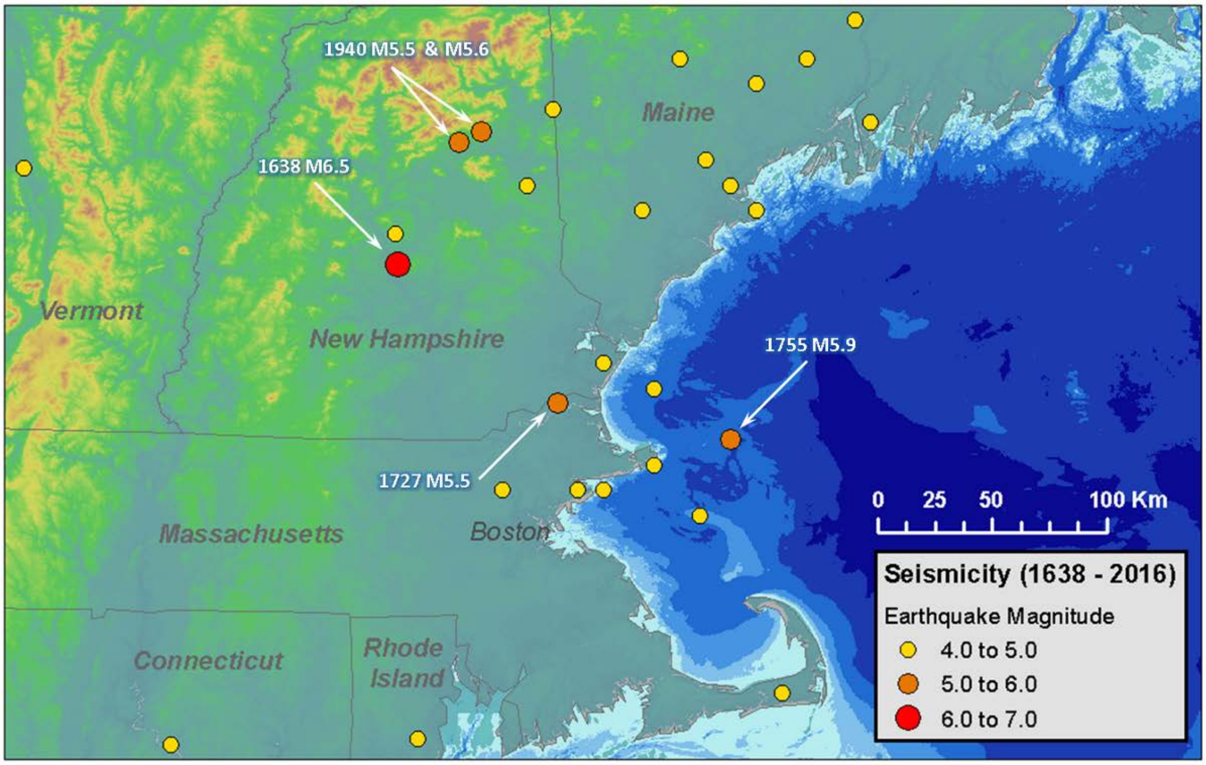

Fig. 1 – Seismicity near Boston, MA, USA (earthquake data from [10, 11]).

3. Vulnerability of Buildings in Metro-Boston

Boston is one of the oldest cities in the US. There are many 19th-century Victorian brownstone homes and a great value is placed on the numerous architecturally and culturally significant buildings in the Boston area. Many of these buildings are unreinforced masonry (URM) structures that were shown to be very susceptible to damage or collapse during numerous earthquakes in California and across the world. These URM buildings house not only residential, commercial, and culturally significant historical buildings but also fire stations, police stations, and schools. More than 50% of the housing units in Boston were built before 1940 [7] and it has the highest proportion of pre-1940 housing units among the major cities in the USA [13]. These units were built before any seismic requirements existed in the local building codes many of which even pre-dated any building code requirements or design standards provisions.

Even more recent buildings constructed in the 1960s and early 1970s were built without seismic design considerations. The vulnerability of these buildings is compounded by the fact that many of them are built at locations underlying deep deposits of alluvium floodplains, estuarine deposits, marsh deposits and artificial fill. Many neighborhoods and areas of Boston today used to be tidal marshes before being filled over the course numerous land reclamation projects that started in 18th and 19th century and continued all the way to 20th century [14]. Fig. 3 shows areas of metro-Boston which are filled. The methodologies and materials used to fill these areas vary significantly. Although most areas are filled by gravel and sand which was brought by horse-drawn carts or trains, there are some areas that were filled using garbage, dredged materials, and coal ashes.

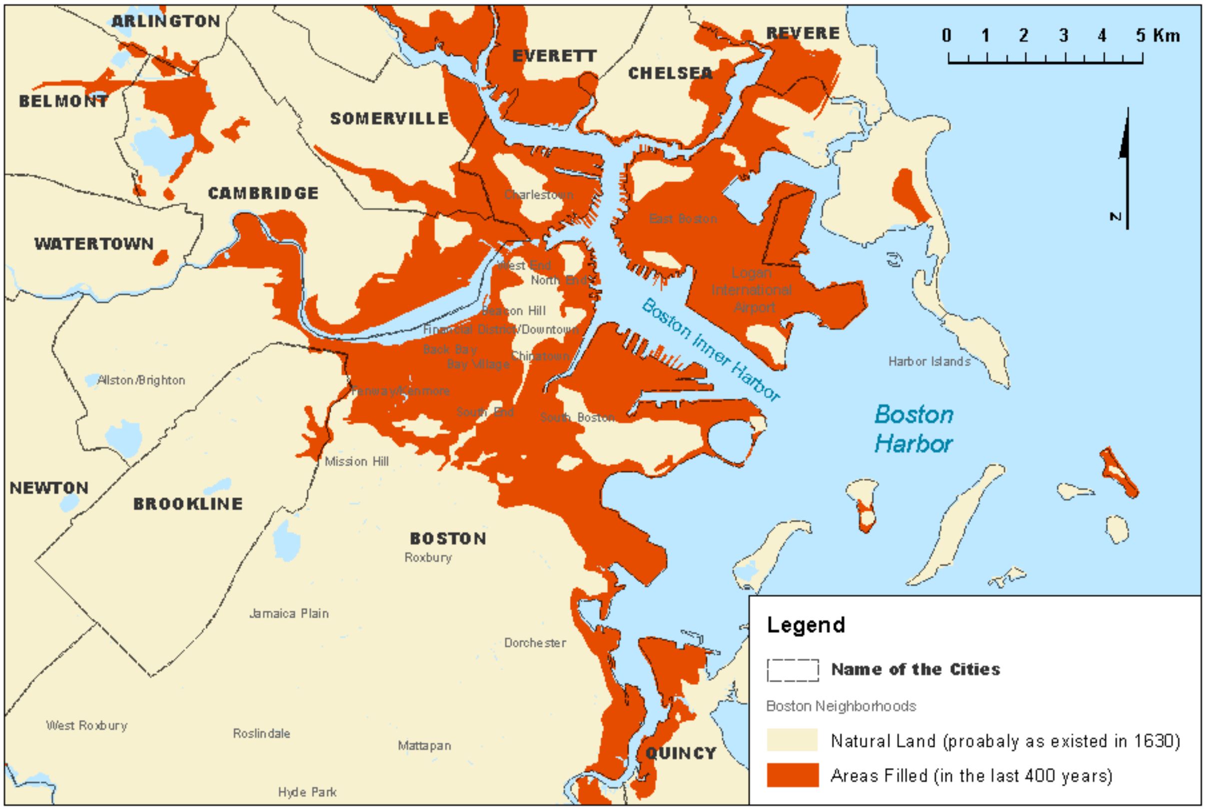

Fig. 3 - Map depicting areas of Boston and adjacent cities filled in the last 400 years (after [15]).

It has been observed and documented in numerous earthquakes across the world that buildings constructed upon land that is underlain by fill material are not only affected by higher ground shaking due to site amplification but also by earthquake-induced liquefaction. Damage observed in the Marina district in San Francisco during 1989 Loma Prieta Earthquake, and Urayasu City during 2011 Tohoku Earthquake [17] are only few examples. Areas located along the Charles River or other streams and coastal areas of Boston, Cambridge, Somerville, Everett, Medford and other cities are at particularly higher risk due to the presence of deep soil deposits which can have a dramatic effect on earthquake ground shaking as well as loose filled materials which were placed with no proper engineering compaction. Fig. 4 shows selected soil profiles at three neighborhoods in the City of Boston with deep deposits. The thickness and quality of fill, organic deposits, and marine deposits vary significantly from place to place.

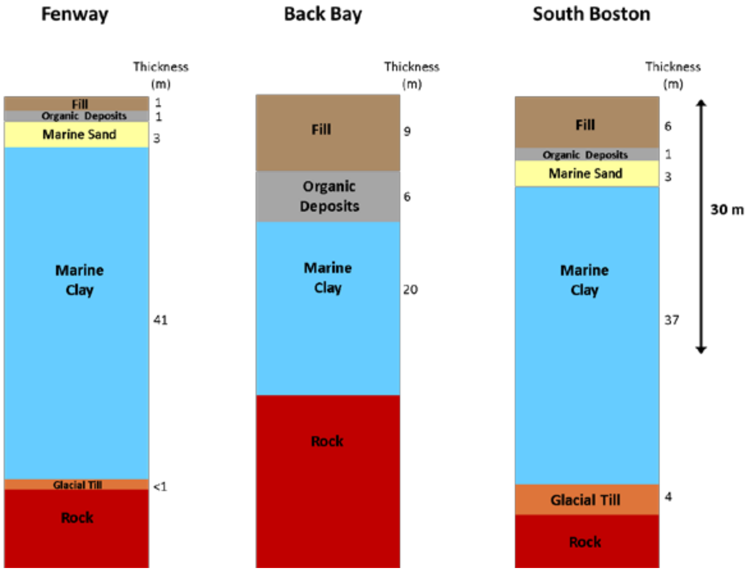

Fig. 4 – Selected soil profiles in three neighborhoods in the City of Boston showing deep soil deposits and various thickness of fill.

In Boston, areas filled by dumping dredged or transported material into water, or by hydraulic filling are particularly more susceptible to liquefaction. The South Boston flats, Atlantic Avenue, Back Bay neighborhood were filled by dredged material. Hydraulic dredge materials were used to fill the South Boston flats, the Bay State road area, areas around North Station, and the Cambridge side of Charles River where the MIT campus (Massachusetts Institute of Technology) currently resides. Logan International Airport was also created by hydraulic filling which later covered with sand, and paved to create the runways. However, the hydraulic fill was mostly consisted of chunk of clay which has settled considerably since its placement in the 1940s [14].

Most structures in Back Bay and other neighborhoods in Boston, which were constructed in filled areas during the late-19th and early-20th century are supported on wood piles, driven to bear on the dense sand layer below the organic deposits or to the clay as friction piles [17]. The relativity deep foundations make these older buildings less vulnerable to liquefaction if ground deformation occurs. However, the reduction in water infiltration and dewatering for various tunnels and draining systems has exposed these untreated piles to drying and decay and in some areas they may no longer be structurally sound to support the above structure in an event that soil loses its bearing capacity due to liquefaction or cyclic softening in clay.

4. Seismic Provisions of Massachusetts Building Codes

The 8th edition of the Massachusetts State Building Code (MSBC) is the building code that has been in effect in the Commonwealth of Massachusetts since early 2011. It is based on 2009 International Building Code (IBC) published by the International Code Council (ICC) with separate amendments published by the State Board of Building Regulations and Standards [18].

Prior to 1975, before the first edition of the State Building Code became effective, each municipality in Massachusetts had different building codes suited to their own needs. The first building code for City of Boston was published in 1873. The first code with seismic provisions was the 1970 edition of Boston Building Code which is based on UBC 1967 (Uniform Building Code) [19]. Although UBC 1967 put Boston and surrounding areas in Zone 3, the 1970 Boston Building Code required that all structures except one and two dwelling family dwellings be capable of withstanding the lateral forces prescribed for Zone 2 of UBC 1967.

The first State Building Code became effective on January 1, 1975. The second edition, which became effective in 1976, included seismic design provisions which followed the seismic provisions of UBC with some modifications. From 1990, the MSBC followed BOCA (Building Officials Code Administrators) code more closely with seismic provisions similar to UBC requirements. Since then the MSBC has followed the most current provisions of UBC and IBC with several years delay between publication and adoption by the state. The seventh edition which became effective in September 2008 is the first code based on IBC.

Differing from its contemporary UBC provisions, one major component of early MSBCs was its prescriptive requirements for liquefaction consideration. In the first edition of MSBC (1975), it was required that earthquake liquefaction potential of saturated medium and fine sands be evaluated. A series of curves relating Standard Penetration Resistance (SPT N-value) and depth below ground surface be provided for various groundwater depths to determine if the soil is susceptible or not susceptible to liquefaction. For susceptible sites, a criterion based on the total thickness of liquefaction-susceptible soil and depth to top of liquefaction-susceptible soil was put in place permitting no other action if the criterion was met. The requirements for liquefaction evaluation remained in place until changes were enacted 1990, and 2008. In the later codes the criteria is described as a screening tool whereby if the criteria are not met, appropriate studies, analyses, and designs shall be made by a registered design professional to determine that the structural loads can be safely supported.

5. Shear-Wave Velocity Map

As part of this study a new shear-wave velocity map was developed for Metro Boston. The new map is developed based on 1:24,000 surficial geology maps of Boston area [15] and a database of in-situ shear-wave velocity measurements and borehole logs. The in-situ shear-wave velocity measurements were available at 41 locations. The measurements obtained from various investigation, engineering and design reports for the Central Artery/Tunnel Project (CA/T), known unofficially as the “Big Dig” Project in Boston, and data collected by Thompson et al. [5]. Additional information considered in developing this map includes depth to bedrock and thickness of younger deposits and Artificial Fill. Fig. 5 shows the V_{S30} map of Metro-Boston and the location of site-specific shear-wave velocity measurements used to validate and calibrate the map.

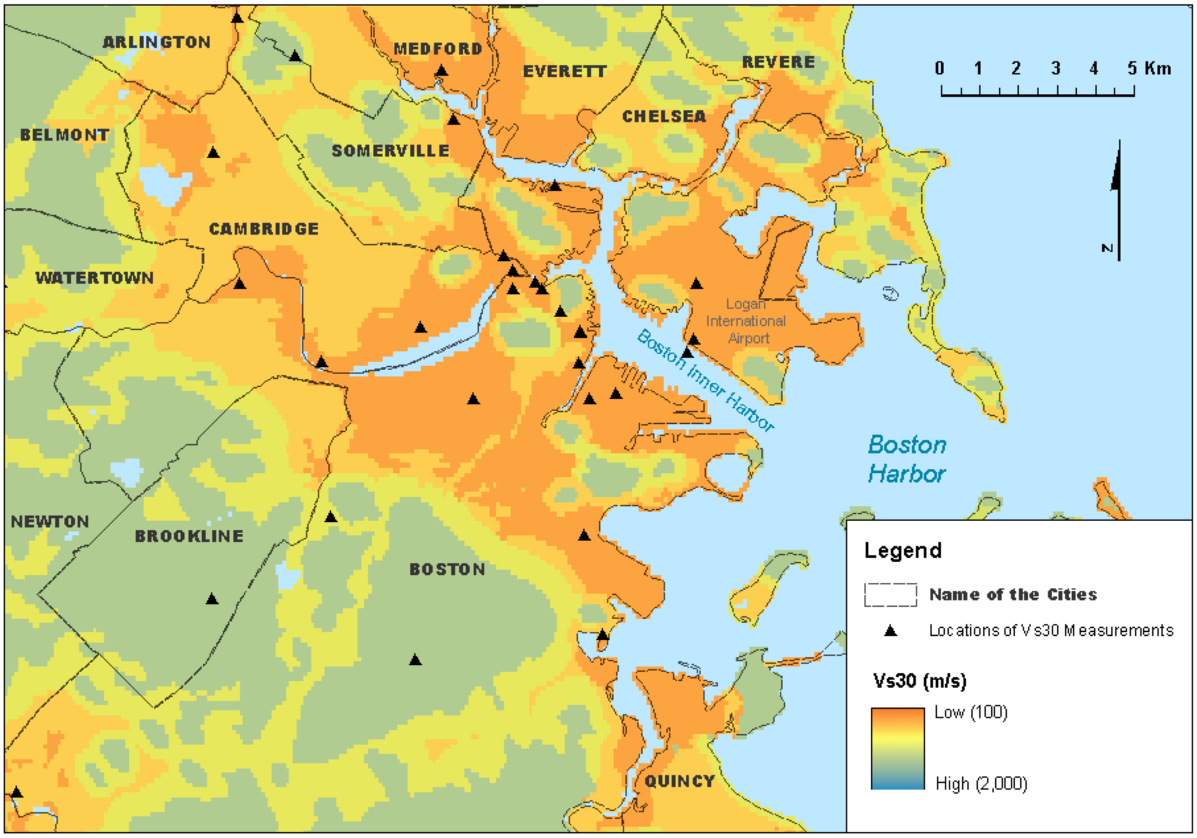

Fig. 5 – Shear-Wave Velocity of Metro-Boston.

6. Building Inventory

A database containing the inventory of all properties at risk, their important characteristics (including the structural type, construction material, occupancy, height, floor area, and number of occupants), and their replacement values (cost associated with reconstruction of that property) is collected and maintained by AIR Worldwide. The sources for this proprietary database include various government organizations and private vendors. To keep the size and resolution of the regional loss estimation on a manageable scale it is necessary to group the exposures in some reasonable geographical units. This study is performed using AIR's 90-meter resolution building inventory database in Massachusetts. Infrastructures (such as roads, highways, bridges and pipelines) are not included in this study.

Our study was focused on six counties of eastern Massachusetts including Suffolk (which includes the City of Boston), Bristol, Essex, Middlesex, Norfolk, and Plymouth Counties. In terms of the replacement values in this region, the single and multi-family wood-frame houses in the suburban neighborhoods are most prevalent in the inventory. It is followed by low-rise, mid-rise, and high-rise steel buildings which are the predominant construction for the commercial buildings in Greater Boston. Masonry buildings are the third most prevalent within the inventory with more than 100,000 different properties classified in this construction category.

7. Earthquake Scenarios

In this study, four plausible earthquakes are selected for assessment. These case studies are intended to provide a historical perspective as well as some estimates of likely damage from probable events with a 2% probability of exceedance in 50 year, consistent with the provisions of current Massachusetts State Building Code [18].

The first selected event (Scenario A) is an earthquake similar to the 1755 Cape Ann earthquake which provides a historical perspective if that event were to impact the built environment as it exists in Boston today. An estimation of its likely location, depth, and magnitude is selected from a range of reasonable values to simulate ground motions consistent with the damage observations in Boston in 1755, which is believed in the range of 0.08 g to 0.13 g in terms of PGA [1,3]. This criterion is particularly important for a study to re-create a historical event because it can reduce combined uncertainties among magnitude, location, depth, attenuation and soil amplification.

Additionally, probabilistic events are simulated from a magnitude-recurrence perspective by which events with a magnitude Mw = 5.9 are uniformly distributed spatially within a 100 km radius of downtown Boston. From over 30,000 simulated events, one is selected which results in damage close to the average damage from all 30,000 simulations and ground motion intensity (spectral acceleration at short periods, Ss) in Boston close to the design code requirement of 0.29g on BC rock (Scenario B). This hazard level corresponds to the spectral response accelerations of probabilistic Maximum Considered Earthquake (MCE) as defined by 8th edition of MSBC [18].

Furthermore, to provide a realistic worst-case perspective, similar 5.9 magnitude events are simulated and uniformly distributed spatially around two known but inactive faults adjacent to Boston, the Northern Fault and the Pompanoag Fault (Scenario C and D). One simulated event is selected from each fault which results in damage close to the average damage incurred by simulated events around that fault and ground motion intensity close to the design code shaking requirement for Boston.

Table 1 provides a summary of selected scenarios and their description. The epicenters of the selected scenarios are showed in Fig. 6.

Table 1: Description of selected earthquake scenarios.

Scenario	Name	Description
A	Historical Scenario	Similar to 1755 Cape Ann Earthquake that results in ground motions in downtown Boston conforming with observed damages.
B	Building Code Compatible Scenario (2,500 years return period)	M5.9 within 100 km radius of downtown Boston which causes spectral acceleration at short periods, Ss of 0.29g in the city of Boston with 2% probability of exceedance in 50 years (2,500 years return period) based on MSBC and result in a mean loss out of all plausible scenarios.
C	Northern border Fault Scenario	M5.9 with criteria similar to Scenario B but with an epicenter along inactive Northern border fault.
D	Ponkapoag Fault Scenario	M5.9 with criteria similar to Scenario B but with an epicenter along inactive South Ponkapoag fault.

Fig. 6 – Epicenter of selected earthquake scenarios (gray circle indicates Downtown Boston).

8. Ground Motions

In order to estimate the damage and losses induced by the four selected scenarios at locations where there is property at risk, ground motion intensities (including PGA and spectral acceleration at various periods) were determined. Using a weighted average of ground motion prediction equations (GMPEs) or attenuation relationships (which provide the intensities as a function of the magnitude, distance, and rupture mechanism of the earthquake), local ground motion intensities were calculated. The local site conditions were considered by applying site amplification factors based on the newly developed shear-wave velocity map for the eastern Massachusetts. Table 2 summarizes the calculated ground motion intensities at the ground surface in downtown Boston and surrounding neighborhoods.

Table 2 – Magnitude and distance of earthquake scenarios and range of calculated ground motion intensities in downtown Boston and surrounding neighborhoods.

Scenario	**A**	**B**	**C**	**D**
Mw	6.3	5.9	5.9	5.9
Distance, km*	63	28	20	19
PGA (g)	0.07 to 0.10	0.17 to 0.25	0.23 to 0.37	0.21 to 0.34
Sa,0.3 (g)	0.12 to 0.19	0.22 to 0.40	0.29 to 0.59	0.27 to 0.51
Sa1.0 (g)	0.03 to 0.07	0.05 to 0.10	0.06 to 0.16	0.06 to 0.14

* Distance from downtown Boston.

9. Damage and Loss Estimation

The Earthquake Model for this study captures the effects of ground shaking and liquefaction damage on properties. The loss estimation for ground shaking employs the AIR Earthquake Loss Estimation framework which is described by [20]. In this framework for damages due to ground shaking, damage functions correlate hazard intensity with expected monetary damage as defined by the ratio of repair cost to replacement value. As part of this study, the vulnerability of low-rise URMs were studied in more details and new set of damage functions were developed.

For earthquake-induced liquefaction, a new liquefaction model was implemented. The liquefaction intensity calculation of the module follows methods summarized by [21] and [22]. Input data for the liquefaction module include the depth of the groundwater table, liquefaction susceptibility map, along with representative soil profiles.

During the development of the liquefaction module, AIR collected and developed depth to groundwater table maps based on more than 7000 observations from Boston Groundwater Trust, Central Artery and Tunnel project, USGS, and other local sources. A new liquefaction susceptibility map was also developed based on the surficial geology and borehole data, providing stratification and soil properties in the region, which allowed evaluation of relative liquefaction susceptibility for this area. The 7 susceptibility levels identified include Very Low, Low, Moderate Low, Moderate, Moderate High, High, and Very High. Assuming that relative susceptibility is consistent within each level, representative soil profiles were assigned to each susceptibility category.

The building damage resulting from liquefaction was modeled as a function of permanent ground displacement, which causes damage when the building becomes vertically displaced due to post-liquefaction differential settlement. To determine vertical ground displacement, the relationship between factor of safety and volumetric strain are used. Data from the Earthquake Commission (EQC) of New Zealand from the 2010 and 2011 Canterbury Earthquakes in addition to data from the 2011 Tohoku Earthquake in Japan were used as the basis for the damage functions developed to estimate the vulnerability of buildings to settlement. The Liquefaction Potential Index (LPI) is also calculated and used to estimate the likelihood of liquefaction at a given location.

The estimated economic losses and casualties for the selected scenarios within six counties in the eastern Massachusetts are reported in Table 3. All four plausible earthquakes demonstrated the potential to cause significant economic losses and casualties in the region. Although, our analysis was focused on six counties in eastern Massachusetts, based on the hazard footprint we do not expect significant losses from other counties in the state or from the nearby states of New Hampshire, Rhode Island, or Maine. The reported numbers includes building, content, and business interruption losses which includes damage to residential, commercial, industrial, municipal, and educational occupancies as well as utility and transportation facilities but does not include damage to infrastructures and lifelines.

Table 3 – Estimated economic losses and casualties.

Scenario	**A**	**B**	**C**	**D**
Property Loss (Billion USD)	8.5	17.4	60.9	46.7
Fatalities	21	75	435	330
Casualties *	1,166	2,133	17,443	13,766

Notes: * Not including fatalities.

10. Discussion and Conclusion

The effect of shake and liquefaction damage for four (4) earthquake scenarios in the Boston area is estimated and presented in the previous section. Our evaluation shows that all four plausible earthquakes could cause significant economic losses and loss of lives in the Boston area. While the 1755 Cape Ann earthquake is regarded as a significantly devastating scenario for the Boston area, an event with a design code level recurrence and intensity can be expected to inflict tens of billions of dollars in economic losses. The heavy losses in Boston are mainly due to close proximity to the earthquake source and its high concentration of old buildings which were built without seismic considerations.

A detailed evaluation of loss suggests that residential properties account for more than 50% of the monetary loss, followed by commercial and industrial properties for all the scenarios. However, in the City of Boston commercial and industrial property damage dominates the loss because of more commercial and industrial properties within the city limits. Among various construction classes, more than half of loss in in the six counties is due to damage to wood-frame buildings. Considering that majority of houses in these areas are made of wood with no seismic design considerations, this level of loss was anticipated. However, among the different construction classes, URMs were shown to be the most vulnerable buildings with average damage ratio of 20% in the affected areas. This level of widespread damage could result in collapse of several URM buildings which is a leading factor contributing to severe injuries and fatalities for the selected scenarios.

Property damage due to liquefaction is considerable but not as severe as what was observed in New Zealand during the 2010 and 2011 earthquakes. The following reasons can explain the low level of liquefaction damage to property: 1) The thickness and quality of artificial fill or other liquefiable strata in Boston Area varies significantly from location to location which limits the extent of liquefaction, 2) The subsurface soil includes deep deposits of clay and organic materials which are not susceptible to liquefaction, 3) Simulated ground motions in Boston are generally lower because of smaller magnitude earthquakes considered in this scenario study, and 4) Most buildings built on fill are being supported on timber piles, which reduced its chance of damage to liquefaction compare to buildings supported on shallow foundations.

Nonetheless, South Boston, the Seaport District, the Cambridge side of the Charles River, coastal areas of Charleston and areas along the Mystic River were shown to exhibit extensive liquefaction. The possible damage to buildings due to liquefaction-induced settlement is low; however, liquefaction damages to utilities, roads and aging infrastructures could be significant, where the extent of damage could have a profound effect on the resiliency of the city after such an event. Fig. 7 shows liquefaction likelihood for Scenario C in the Boston Area.

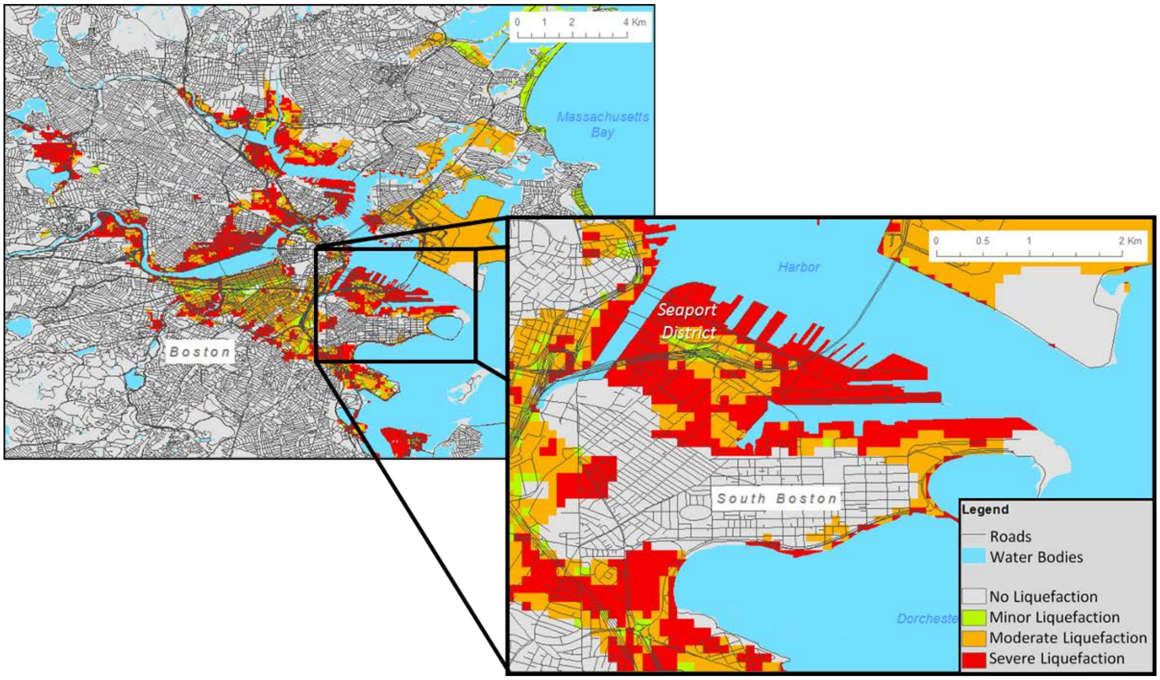

Fig. 7: Liquefaction likelihood for Scenario C in the Boston Area.

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