Observational Evidence for Amplification of Earthquake Ground Motions in Boston & Vicinity

Using newspaper reports of the felt effects of an earthquake can provide a basis for estimating what areas might experience damaging ground shaking in future earthquakes.

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Boston is a major metropolitan area that lies in a region of moderate seismic hazard along the east coast of the United States. The Boston area includes extensive areas of landfill that have greatly expanded the surface area of the city. Soil layers, including landfill, are known to be capable of amplifying earthquake ground shaking in some cases. A total of 179 felt reports taken from published articles from local newspapers from eight earthquakes were analyzed. Almost all of these reports were from the earlier half of the twentieth century when the journalistic style included much site-specific information on felt effects. Newspaper reports for earthquakes in the past few decades provided less such site-specific information. Several landfill areas — including Back Bay, the former Great Cove area downtown, South Boston and parts of Cambridge — experienced ground shaking that averaged almost 1 modified Mercalli intensity (MMI) unit over that expected in Boston for these earthquakes. Some other areas not located on landfill also seemed to experience amplified ground shaking (especially Beacon Hill and Harvard Square in Cambridge). On the other hand, there is no evidence of the amplification of ground shaking on drumlins in Brookline or on bedrock areas.

Background

There is currently great interest in defining urban seismic hazards for those U.S. cities at

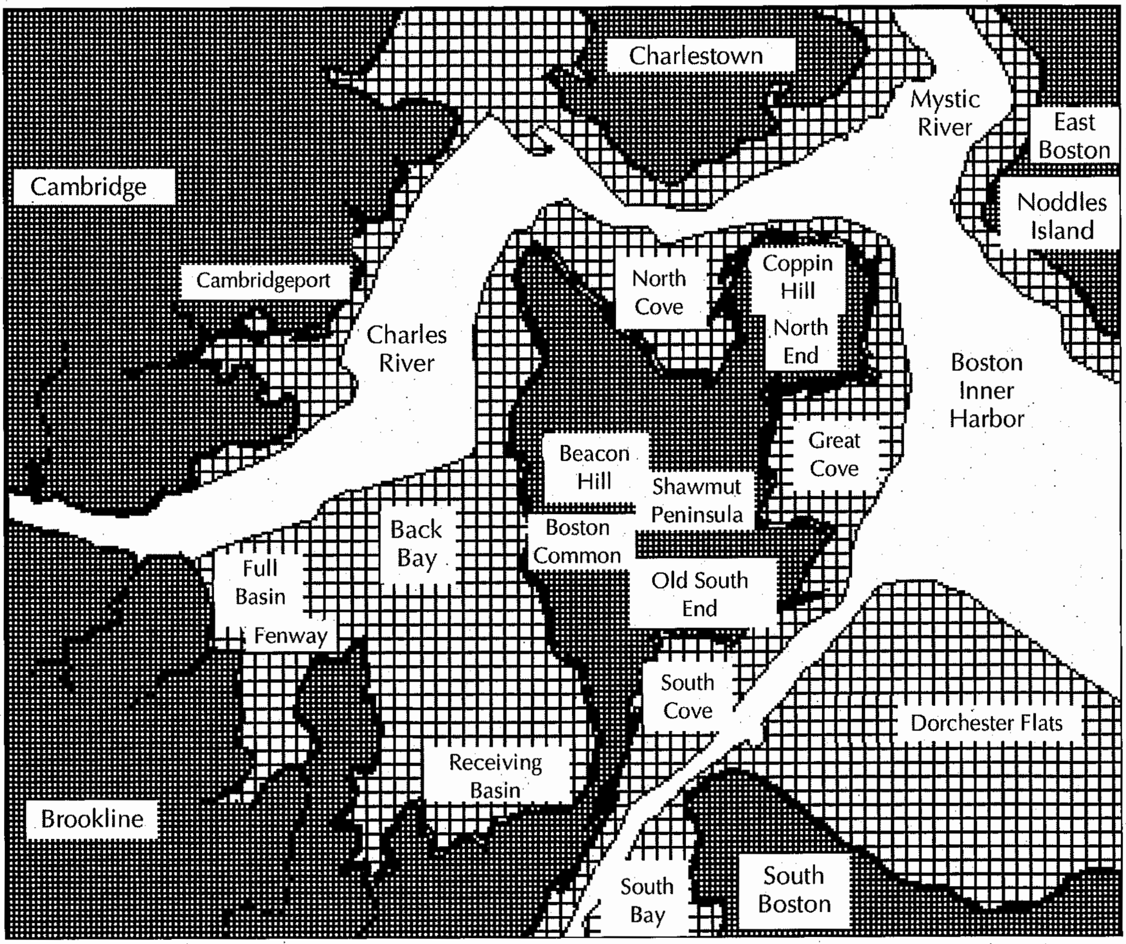

FIGURE 1. Map showing the pre-colonial (dark-hatched) and the modern (light-hatched) land areas of Boston and vicinity.

risk from earthquakes. While the seismic hazard at national and regional scales have been determined with some level of confidence,[1] a refinement of the understanding of seismic hazards and risks in urban areas is now needed so that estimates of the possible losses in future earthquakes can be made with a high level of accuracy. Earthquakes such as the Loma Prieta earthquake in California in 1989, an event that caused major damage on unconsolidated soil areas (especially landfill) in San Francisco and Oakland, have driven home the point that there can be great local variations in earthquake ground motions due to spatial variations in soil conditions.[2] Among other things, assessing possible earthquake losses in urban areas requires that the distribution of soils that can amplify ground motions, or that may be susceptible to liquefaction, needs to be known. The software program HAZUS, developed and distributed by the Federal Emergency Management Agency (FEMA) for computing earthquake losses, is capable of utilizing maps of soil types and properties in making loss estimates.[3] Thus, the emphasis on urban earthquake hazard studies has the practical application of providing important input information for HAZUS users.

The cities of San Francisco, Oakland and Los Angeles have been shaken by strong earthquakes during the last century. Instrumented recordings of the strong ground motions from such earthquakes, combined with the spatial patterns of damage, have given strong observational evidence of which areas in these cities are prone to amplifying earthquake ground motions. However, for cities in the eastern U.S., where there is some hazard from earthquakes, there have been no strong earthquakes nearby during the last hundred years that have caused extensive damage or had their ground motions recorded instrumentally in the cities themselves. For these cities, other evidence must be used to infer which areas are prone to ground-shaking amplification and how much amplification they may experience.

In the case of the Boston urban area, there are extensive areas of man-made land that may likely experience at least some level of ground-shaking amplification in earthquakes. In colonial times, what is now downtown Boston was originally the Shawmut peninsula, a hilly protrusion of land connected by a narrow land bridge to the mainland (see Figure 1).[4,5] The Shawmut peninsula was surrounded on the west by the Charles River estuary, on the north by the Mystic River estuary and on the east by Boston Harbor. It was on this peninsula that the colonials founded Boston. In the early nineteenth century, the inhabitants of Boston began to fill in areas around the Shawmut peninsula to increase the land area of the city, initially using glacial sand and till from the hills in the center of the city as the fill material but later bringing in fill from other areas. Throughout the nineteenth and the beginning of the twentieth centuries, the land surface of the city was expanded as more areas were filled in. By 1920 the modern configuration of the city had been essentially completed, with downtown Boston having about three times the surface area of the original Shawmut peninsula. Other parts of the Boston metropolitan area — such as East Boston, South Boston, Dorchester Flats, Cambridge and Charlestown — also were extended by the construction of landfill areas.

With all of this modification to the original landscape in Boston and vicinity, the potential exists that a strong earthquake near Boston could be associated with extensive areas of damage due to ground-shaking amplification or liquefaction on these filled areas and in other parts of the metropolitan area. Because there have been no damaging earthquakes centered near Boston since the landfill areas were created, a determination of which ones may be susceptible to ground-shaking amplification must be made based on indirect evidence. The record of felt effects from distant earthquakes is one indirect method that can be used to indicate the potential spatial distribution of ground-motion amplification in the area. During the twentieth century there have been a number of earthquakes that have been felt throughout the greater Boston area. These events were widely reported in local newspapers, and these newspaper reports can be used to form the observational basis for determining the susceptibility to ground-shaking amplification.

Twentieth-Century Earthquakes Felt Throughout the Greater Boston Area

Table 1 lists the earthquakes for which Boston newspapers were scanned for information on their felt effects in the Boston area and Figure 2 shows the locations of these events. The events from the first half of the century yielded much more abundant data than those events in the 1980s due to the journalistic styles in vogue at different times. For the 1925 and 1935 earthquakes, there are numerous detailed reports that are quite specific about both the location and what was felt. The earthquakes in the 1940s contained descriptions of felt effects along with analyses by experts explaining where the earthquake epicenters were and why they occurred. However, paper rationing during World War II limited the space allotted to reporting the earthquakes. By the 1980s the newspaper reports of the earthquakes were dominated by summary statements of the effects of the earthquakes in the area and by extensive coverage of analyses of the earthquakes by local scientists. Relatively few detailed reports of the felt effects of the earthquakes in this period were found in the newspapers. For this reason, no site-specific felt reports for Boston for the January 9, 1982, earthquake in central New Brunswick, for the January 18, 1982, earthquake in central New Hampshire, or for the October 7, 1983, earthquake from New York State were found even though all three were widely felt in the Boston area.

TABLE 1.
Earthquake Event Dataset

Locality	Date	Time	Magnitude (m_b)	Distance to Boston (km)	Expected MMI at Boston	Number of Observations	MMI Range
Charlevoix, PQ	1925/02/28	9:19 pm	6.6	604	IV	108	II-VI.5
Timiskaming, PQ	1935/11/01	1:03 am	6.2	803	III	8	IV.5-V
Ossipee, NH	1940/12/20	2:27 am	5.5	165	V	16	II-V.5
Ossipee, NH	1940/12/24	8:43 am	5.5	165	V	23	II-V
Massena, NY	1944/09/04	11:38 pm	5.8	408	III	10	II-V
Marblehead, MA	1963/10/16	10:30 am	3.8	56	IV	4	III.5
Miramichi, NB	1982/01/09	7:53 am	5.8	623	III	0	
Miramichi, NB	1982/01/11	4:41 pm	5.5	623	III	3	IV
Gaza, NH	1982/01/18	7:15 pm	4.7	130	V	0	
Goodnow, NY	1983/10/07	5:18 am	5.1	308	IV	0	
Saguenay, PQ	1988/11/25	6:46 pm	5.9	635	IV	7	II-III.5

Most of the earthquakes were in the magnitude range of 5.1 to 6.6 and were centered several hundred kilometers from Boston. However, one smaller event, a magnitude 3.8 earthquake centered just northeast of Boston on October 16, 1963, was included because it caused great consternation throughout the Boston area. Unfortunately, only a few specific felt reports in the newspapers were found for this earthquake. According to Pulli's intensity-magnitude-distance relation,[6] all of these earthquakes should have caused an MMI between III and V in Boston (see Table 1).

Newspaper Felt Report Dataset

One hundred and seventy-nine site-specific reports were found in the *Boston Globe* and *Boston Herald* newspapers for the earthquakes listed in Table 1. For each report, the MMI was inferred from the published description (see Figure 3).[7] In some cases, determining the MMI was quite easy because the description corresponded clearly with one of the intensity levels. However, in many cases, the descriptions were judged to fit either of two intensity levels. In these cases, an intensity level was assigned that was a half-unit between the two possible levels (*e.g.*, if the intensities were found to be III and IV, the event was assigned an intensity III.5 for analysis purposes). There were also newspaper reports of specific localities where an earthquake was not felt. These reports were assigned an MMI of II.

For the 1925 earthquake, there were some reports of damage to buildings. Plaster was reported cracked at the Riverside Court apartments in Cambridge. This report was assigned an MMI of VI since the amount or the extent of the cracking could not be ascertained. Commonwealth Pier in Boston was also reported to have cracked but, again, there was no detailed description of what happened. This report was assigned an MMI of VI. The most serious damage was a reported building collapse in East Boston. No other details are known, particularly the state of the building prior to collapse. Since there were no other reports of building damage from East Boston, this single report of building collapse was rated as an MMI of VI.5.

To allow the intensity reports from the various earthquakes to be combined into a single dataset, the expected intensity in Boston was computed for each earthquake and then the difference between the observed and expected intensities for each of the observations was determined. The difference between the observed and expected intensities is called the

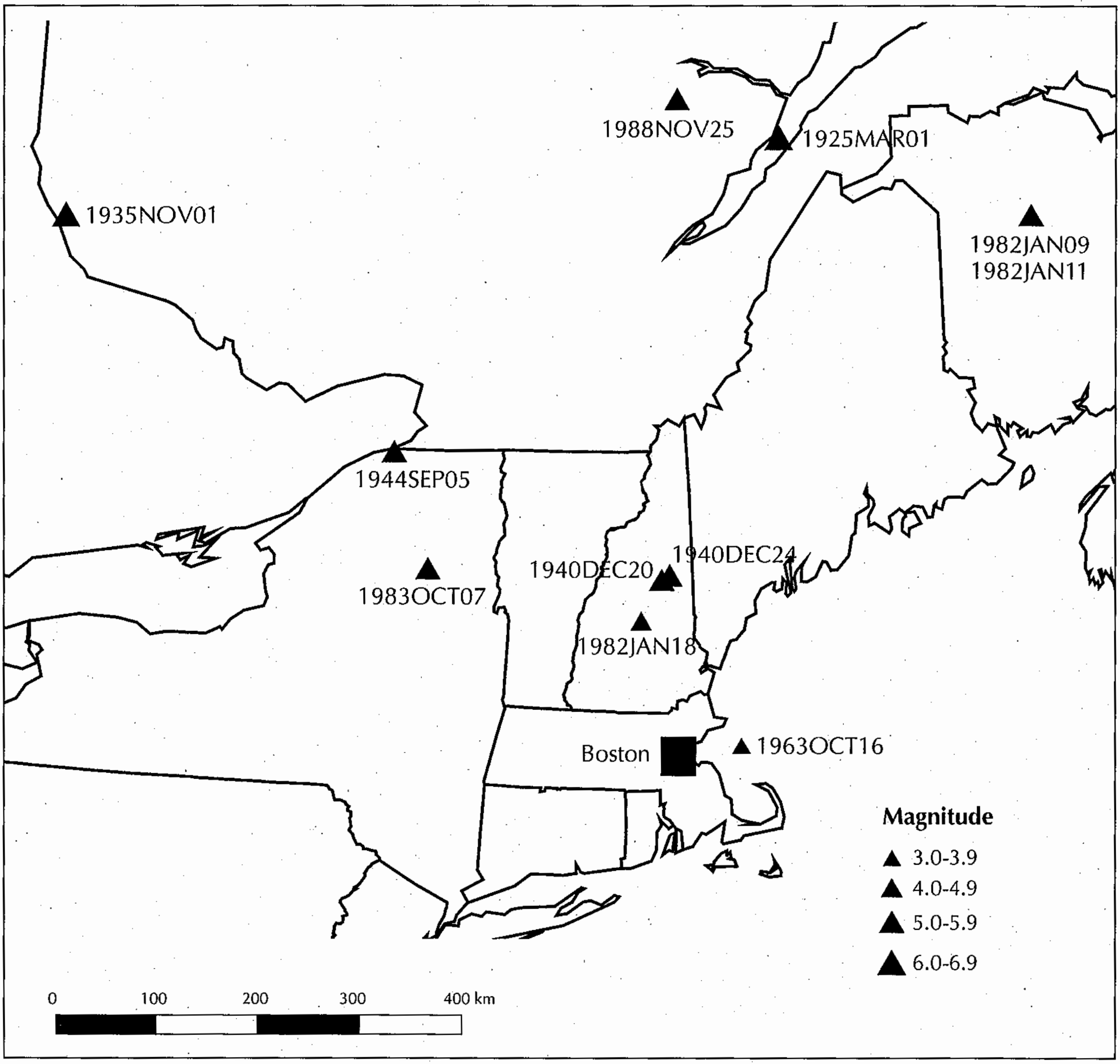

FIGURE 2. Map of the earthquakes for which newspaper felt reports for Boston were sought (also listed in Table 1).

intensity residual. A positive intensity residual means that the observed MMI value was higher than that expected for Boston, while a negative MMI value means that a lower MMI value than expected was experienced. Those localities with positive intensity residuals are assumed to have experienced some local amplification of the bedrock ground shaking due to local soil conditions. The purpose of computing intensity residuals was to construct a dataset that could be used to delineate those parts of the Boston area that consistently experienced ground shaking that exceeded the average expected MMI, thus indicating those areas that may be prone to amplifying the local earthquake ground shaking. The dataset also permits examining whether or not a particular soil condition, especially the landfill areas, are prone to amplifying earthquake ground shaking. In some of the newspaper reports, especially those from the 1925 earthquake, it was suggested that the strongest shaking was felt on the landfill sections of the city.

To compute the expected MMI in Boston for each of the study earthquakes, the intensity-magnitude-distance attenuation relation was used:[6,9]

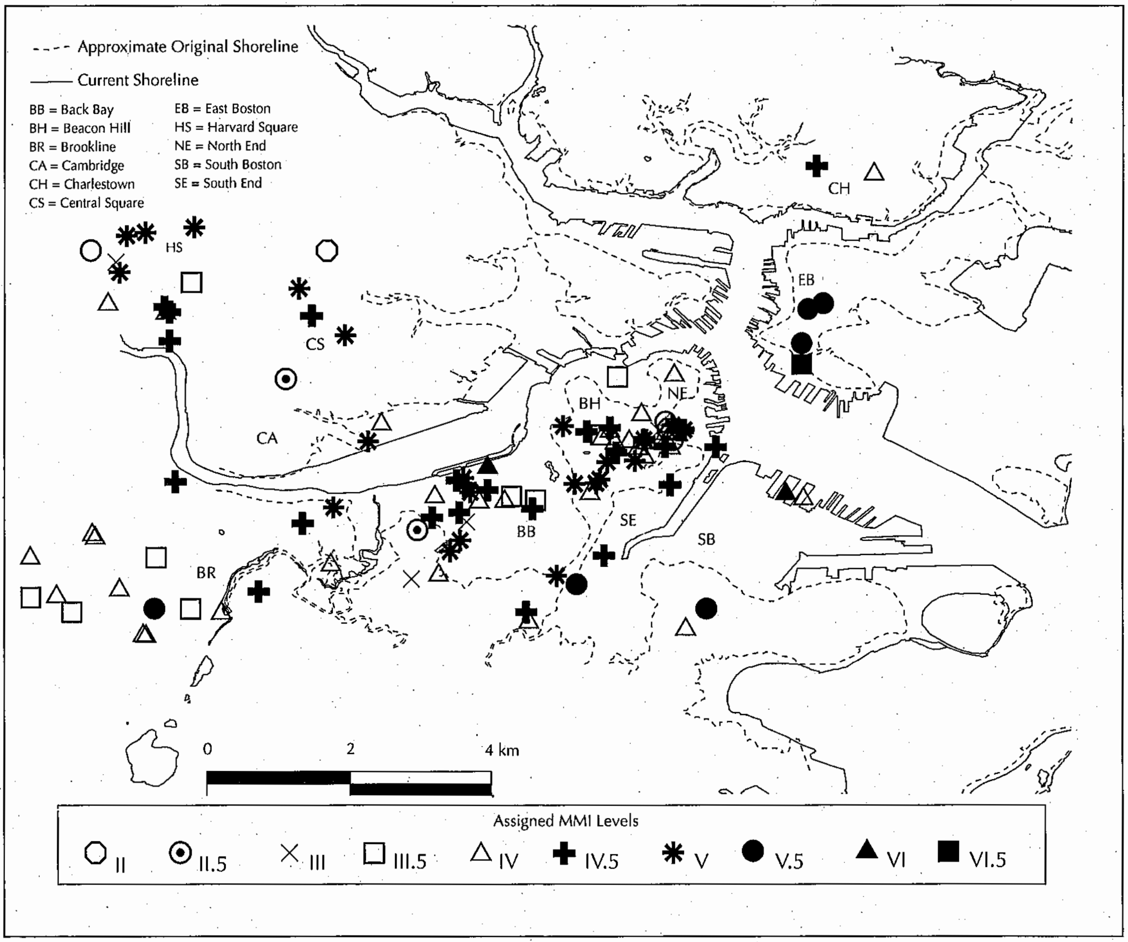

FIGURE 3. MMIs for all of the events in Boston and vicinity from the study dataset.

$$MMI = -1.43 + 1.79\, m_b - 0.0018R - 1.83\, \log10(R)$$

where

m_b = body-wave magnitude of the event
R = epicentral distance in kilometers to the site

This relation was derived from a regression of the mean MMI versus epicentral distance for a dataset consisting of intensity observations for about half-dozen northeastern U.S. earthquakes from 1940 to 1982 ranging in magnitude from 3.5 to 5.8. The MMI value computed from this relation represents the mean intensity value at a distance R given the event magnitude m_b. In applying this equation, the MMI value was computed and rounded to the nearest whole intensity unit before finding the difference between the observed and expected intensities.

Intensity Maps for Boston & Vicinity

Maps of the dataset of intensity residuals for the Boston area and for downtown Boston are shown in Figures 4 and 5. Parts of the area, particularly downtown Boston, have a high density of observations. In other areas, such as around Harvard Square and in Brookline, there is a broad scatter of observations, while there are isolated reports from still other localities. The spatial distribution of the reports is clearly very uneven. Outlines of the original shoreline of the Boston area are also shown in Figures 4 and 5,[4] as is the distribution of surficial geology.[8] The modern shoreline, the original shore-

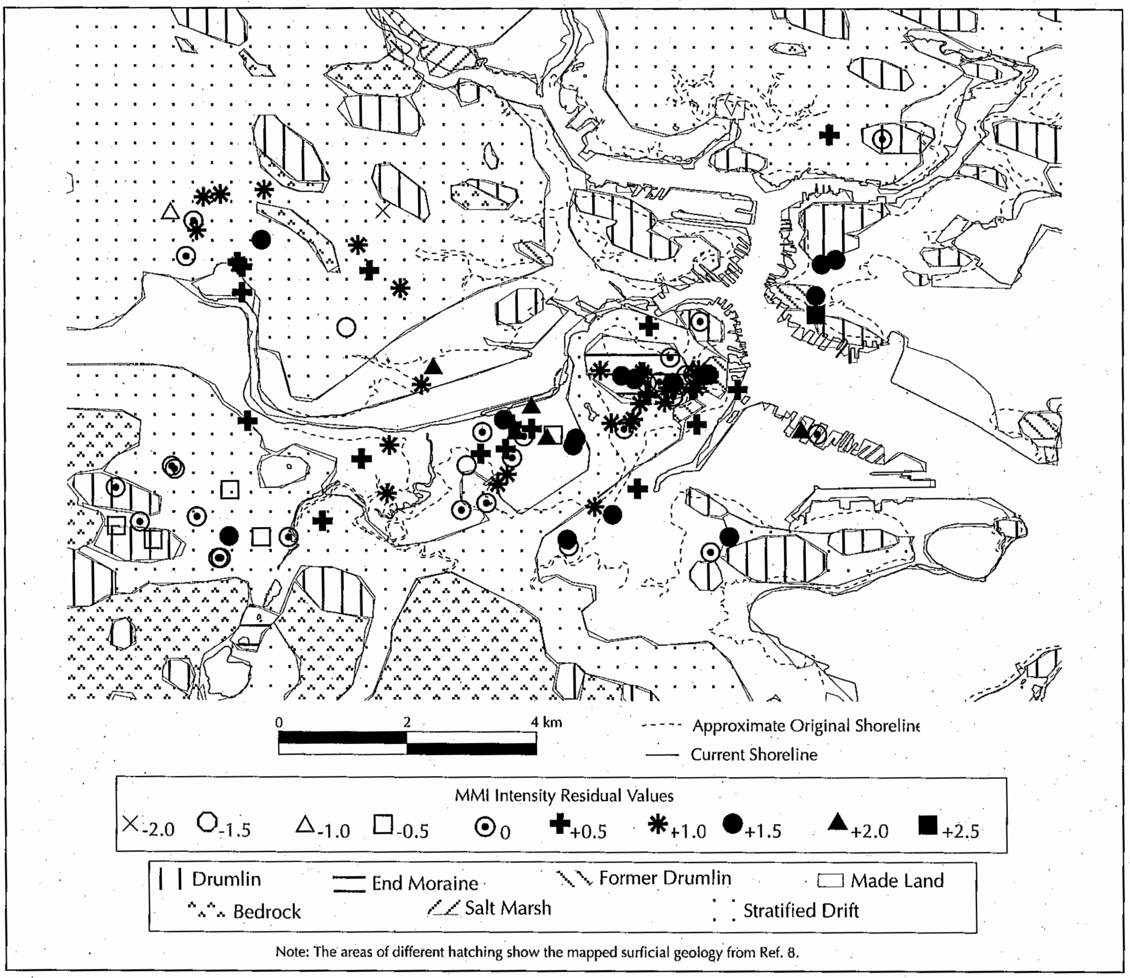

FIGURE 4. MMI residuals for all of the events in Boston and vicinity.

line and the surficial geology were digitized from different base maps and then combined in a common projection in a geographic information system (GIS) program. In the downtown Boston area, the surficial geology map does not register very well with the original shoreline map in many places. This discrepancy reflects the poorer resolution of the surficial geology map as compared to the other two maps.

Figures 4 and 5 reveal some spatial patterns in the intensity residuals in the Boston area. First, it appears that many of the landfill areas have predominantly positive intensity residuals, meaning that these areas probably experienced some amplification of the earthquake ground shaking. The most prominent of these areas — where the most persistent and widespread amplification seems to have occurred — are the Great Cove section downtown (where the Custom House tower and Quincy Market are located), Back Bay, Fenway and the filled-in parts of South Boston. Other isolated reports also reveal areas where the ground shaking seems to have been amplified. The cracked plaster at the Riverbank Courts apartment in Cambridge suggests that the fill areas in that city are susceptible to amplifying earthquake ground motions. The reports from East Boston indicate rather strong local ground-shaking amplification was experienced in the areas just west of Logan Airport along the old shoreline of what was once Noddle's Island.

Some built areas not founded on landfill also seem to have experienced ground-shak-

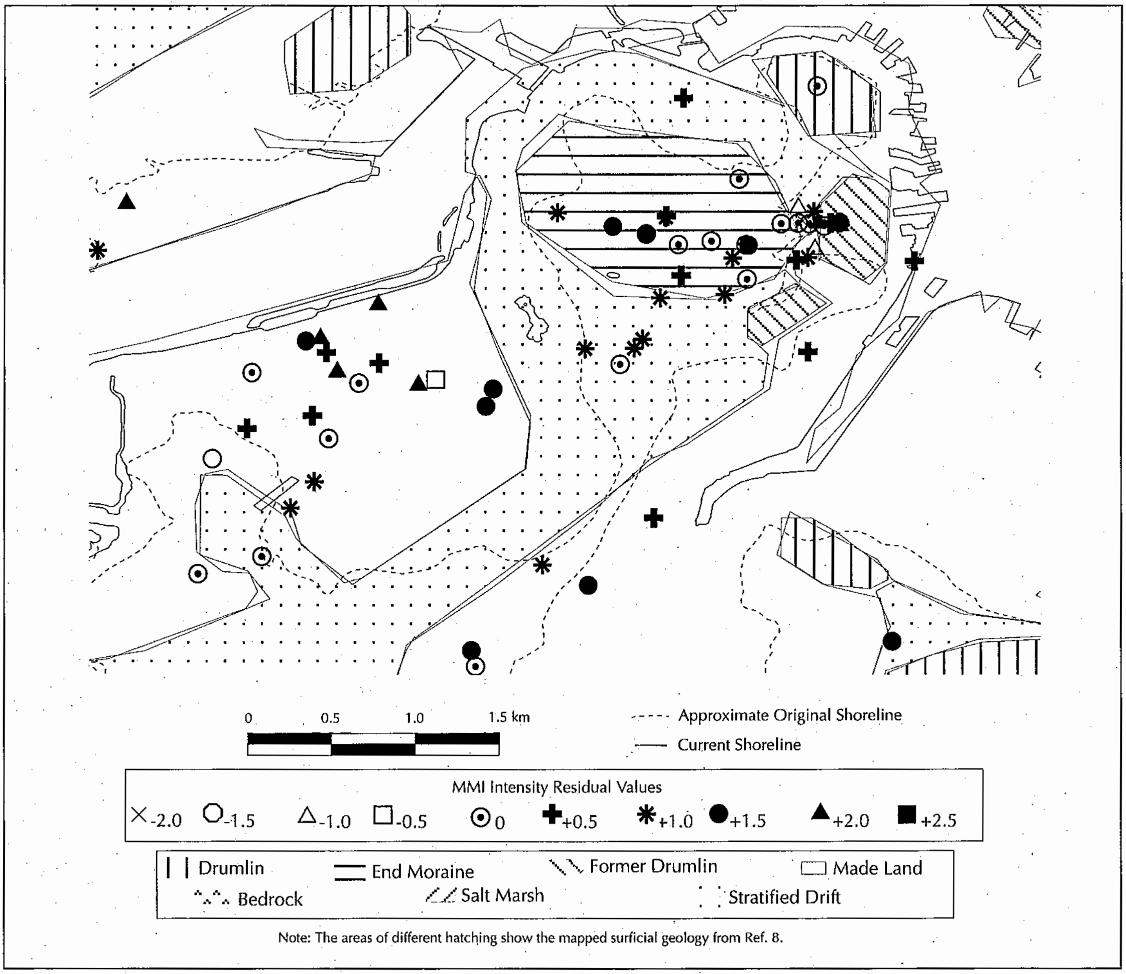

FIGURE 5. MMI residuals for all of the events in downtown Boston.

ing amplification. In the area of downtown, these locations included Beacon Hill and the buildings facing the southeastern side of the Boston Common. These locations are on part of the original Shawmut peninsula. Beacon Hill is the remnant of an end moraine from which the top was removed to use for landfill around Boston, while the section southeast of the Boston Common is primarily clays and till. In addition, there were also a number of positive intensity residuals for several of the earthquakes from the Harvard Square area in Cambridge. Harvard Square itself is situated on a low drumlin. Just west of Harvard Square lies the preglacial course of the Merrimack River, which ran from north to south to the Charles River through the Fresh Pond area. The trend of these positive intensity residuals in this part of Cambridge approximately parallels the ancient Merrimack River course.

Other reports, primarily for the 1925 event, point to other parts of Boston and nearby towns that felt some noticeable measure of earthquake shaking. Central and Inman squares in Cambridge fall into this category, as do localities in Jamaica Plain, West Roxbury and Chelsea.

The Chelsea felt report is from the Bellingham Memorial Hospital where the 1925 shock was experienced with some alarm. The hospital is on a drumlin where the ground shaking was sensed strongly enough to be reported in the newspapers. On the other hand, other drumlins — like those of

Charlestown, Copps Hill in the North End of downtown Boston, and Brookline — either failed to be represented by any felt reports in the dataset or had intensity residuals that were zero or negative. It appears that some drumlins may experience some ground shaking amplification while others do not.

The newspaper reports for the 1925 earthquake note that the earthquake was not felt on bedrock areas. This information is consistent with the dataset, for which all of the reports come from localities on man-made fill areas or on natural sedimentary surficial deposits. Also, the 1925 earthquake was not felt in the Harvard Square subway station even though there were numerous above-ground felt reports in this same place.

To better quantify the intensity residual patterns, average intensity residuals were computed as a function of the type of surficial geology and of geographic area. The results of these computations are listed in Table 2. On average, the landfill areas amplify the ground shaking by almost 1 intensity unit compared with the expected ground shaking. The end moraine area, which in this dataset is represented entirely by observations on Beacon Hill, amplifies the intensity by more than 0.5 intensity unit. Minor intensity amplification is seen on stratified drift areas and, on average, the drumlins experienced no amplification of the intensity values. Spatially, those areas that have average intensity residuals greater than +0.5 include East Boston, the South End, South Boston, Back Bay, Beacon Hill and Harvard Square. Other isolated points of large positive intensity residuals include the landfill area of Cambridge across from Back Bay, the North Cove section of Boston (North Station) and the Central Square section in Cambridge.

TABLE 2.
Mean Intensity Residuals

Surficial Materials	Intensity Residual	Number of Data
Landfill	0.89	33
End Moraine	0.62	21
Stratified Drift	0.28	43
Drumlin	0.08	6

Area	Intensity Residual	Number of Data
East Boston	1.75	4
South End/ South Boston	0.81	8
Back Bay	0.78	27
Beacon Hill	0.62	21
Harvard Square	0.58	12
Brookline (stratified drift areas)	0.13	12
Brookline (drumlins)	0.33	3

Discussion

The newspaper reports clearly indicated that some parts of the Boston area felt earthquakes more strongly than others. Furthermore, many of those areas that were reported to have shaken more strongly in one earthquake were also reported to have shaken more strongly in other earthquakes. For example, there were newspaper reports of greater than average shaking at one or more sites in the Back Bay from the earthquakes of 1925, 1935, 1940 (December 20), 1944, 1963, 1982 and 1988.

Using the maps of the MMI intensity residuals (see Figures 4 and 5), inferences from general statements made in the newspaper reports and the average MMI residuals in Table 2, it is possible to outline those parts of the Boston area that may be prone to some measure of local ground-shaking amplification in future earthquakes (see Figure 6). The areas outlined in Figure 6 indicate those general areas where intensity residuals of 0.5 units or greater were found. In Back Bay, South Boston, the South End (including the former Dorchester Flats), the North Station area and in Cambridge directly across from Back Bay, the areas of possible amplification encompass the extent of the local landfill (assuming that the average intensity residual from the landfill areas not sampled is similar to that for the landfill areas where observations have been obtained).

The possible amplification areas in Figure 6 are the only ones for which data were available. Other parts of the Boston area not outlined in Figure 6 may also be prone to ground-

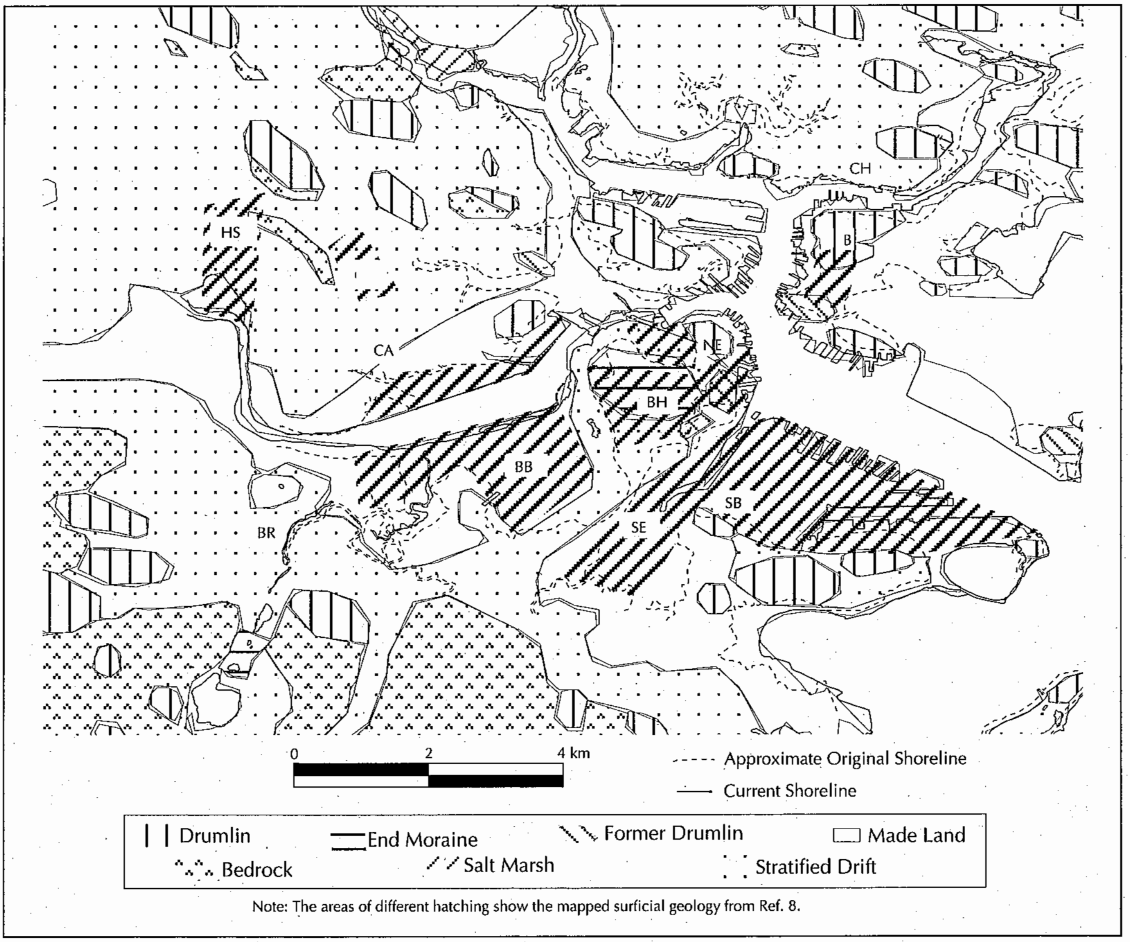

FIGURE 6. Map of those Boston areas (shown by strong diagonal hatching) where some ground-shaking amplification may be possible in future earthquakes. (The map base is the same as in Figure 3.)

shaking amplification, particularly other fill areas. Those areas must be studied using other observational data or using analyses based on geophysical and geotechnical measurements.

The results of this study compare quite favorably with other recent published studies. Haley and Aldrich published maps of soil types in the greater Boston area where minor and major amplification of ground shaking may be expected.[10] These maps were based on soil type and thickness, using the idea that greater amplification may be expected on thicker soils. Wysocki reported on the results of an analysis of a large number of intensity reports collected in Cambridge and vicinity by the Massachusetts Institute of Technology (MIT) for the 1988 Saguenay, Quebec, earthquake.[11] There is a great correspondence between the localities where the 1988 earthquake was reportedly felt in the MIT survey and where the older earthquakes were reportedly felt as noted here. In the Haley and Aldrich and MIT studies, it appears that the landfill areas of Boston and vicinity are at greatest risk for damaging ground shaking in future earthquakes due to local amplification of ground shaking. Some other non-landfill areas, such as Beacon Hill and Harvard Square, may also experience locally stronger shaking. The reasons why these latter areas may amplify earthquake ground shaking are not clear and need further investigation.

Kummer and Kummer *et al.*, who used background ambient noise measurements to determine the predominant period of the soil response and the potential for ground-shaking amplification at about a dozen sites in downtown Boston and vicinity, noted similar results.[12,13] Both of those studies found that the thickest soils and some of the greatest potential for amplification were in the Back Bay area, although other landfill areas of Boston also indicated a potential for some ground-shaking amplification. Those studies also reported some evidence for amplified ground motions on Beacon Hill. Curiously, both of these studies concluded that, in Boston, depth to bedrock was not necessarily a good indicator of how much earthquake ground-shaking amplification may be possible at any given site since the studies found evidence that a site of landfill over shallow bedrock may amplify the ground shaking at some frequencies.

There are a number of limitations of relying on newspaper reports. Clearly, the spatial distribution of the observations is very uneven and does not represent a uniform sample in any statistical sense. Also, since reporters often concentrated their investigations and reporting on large, well recognized buildings (such as the Custom House tower), some parts of the city are overrepresented in the dataset, while many other parts of the city, especially residential areas, are underrepresented. The bias toward reporting felt effects in large buildings also affects the kinds of shaking that the dataset really represents. In general, taller buildings resonate naturally at lower frequencies than shorter buildings. Thus, the reports in the dataset are probably heavily influenced by lower frequency ground motions (probably around 1 to 2 hertz). The higher frequency energy has been attenuated due to the long distance from most of the reported earthquake events to Boston. (It would be expected that the lower frequency energy would dominate the ground motions.) Furthermore, different buildings have different responses to earthquake ground shaking, and the strength of shaking reported at any individual building may be due more to the design and construction of that particular building rather than to a local amplification of the ground shaking in the soil beneath that building.

There is also some uncertainty in the MMI values that were assigned due to the abbreviated form of the felt reports in the newspapers. Typically, the MMI value that was assigned was based on only one element of a report (*e.g.*, people were awakened by the earthquake or items were knocked from shelves). In using the newspaper reports, there can be no absolute consistency of the other felt effects with the assigned MMI intensity and there is no absolute certainty that the reporter was accurate in recording the information that was used in the intensity assignment.

Finally, it must be noted that the bedrock ground motions at Boston for all of these earthquakes were small enough that there probably was relatively little non-linear behavior of the soils. Also, no liquefaction effects were reported for any of these earthquakes.

Even with all these limitations, the accumulated dataset does show that some parts of the Boston area are more prone to experiencing damaging ground shaking in future earthquakes. In particular, the man-made landfill areas of Boston appear to be the most susceptible to amplifying earthquake ground motions. While this conclusion is not new (it was put forth in a map published by Crosby in 1932), it is one that has been reinforced by earthquake after earthquake during the past one hundred years.[14]

Conclusions

The site-specific reports of ground-shaking effects from newspapers are unevenly spaced throughout the Boston area and they encompass reports primarily from earthquakes during the first half of the twentieth century. From the dataset and the analysis of the intensity residuals, it appears that the landfill sections are prone to amplifying bedrock ground shaking by almost 1 MMI unit and other areas may experience some amplification of ground shaking as well. For example, some end moraine and drumlin areas like Beacon Hill and Harvard Square felt locally enhanced ground motions in the earthquakes presented here (although the reasons why these areas seemed to experience some level of ground-shaking amplification is not well understood). A dataset comprising spatially dense sampling from throughout the region would provide a better basis for analysis; however, that dataset must await the occurrence of future earthquakes.

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