THE EFFECT OF LOCAL SURFICIAL GEOLOGY ON THE GROUND MOTIONS OF FUTURE EARTHQUAKES IN BOSTON, MASSACHUSETTS: A COMPARISON WITH SEISMIC CODES

John E. Ebel, Weston Observatory, Department of Geology and Geophysics, Boston College, Weston, USA
Alfredo Urzua, Prototype Engineering, also at Weston Observatory, USA
James Britton, Weston Geophysical Corporation, Lexington, USA

ABSTRACT
Boston, Massachusetts lies where a river estuary and harbor area have been modified by manmade land, where local soils will modify earthquake ground shaking. A GIS database incorporating surficial geology, borehole geotechnical data, and geologic profiles from previous studies was used to create microzonation maps for downtown Boston. The microzonation analysis shows that bedrock peak ground accelerations will be somewhat amplified in many parts of the study area, while those areas of Boston with more than 100 feet of soil could experience a factor of 3 ground motion amplification at 1.0 s period. Earthquake ground motions would fluctuate noticeably across the city. The design spectra from recent building codes in Boston are conservative when compared to the response spectra calculated using a high-frequency input earthquake, but it appears they provide inadequate protection if the input earthquake has significant low-frequency energy. The frequency content of eastern North American earthquakes must be understood for proper microzonation analyses in the region.

RÉSUMÉ
La ville de Boston (Massachusetts) est construite sur des terrains anthropisés repris sur un estuaire et une ancienne zone portuaire, où les sols peuvent modifier les vibrations engendrées par un séisme. Une base de données géoréférencées incorporant des informations sur la géologie des formations superficielles, des relevés géotechniques de forages, et des profils géologiques obtenus lors de précédentes études, a été utilisée pour préparer des cartes de microzonage sismique du centre ville de Boston. Le microzonage montre que les accélérations maximales au rocher peuvent être légèrement amplifiées dans de nombreux secteurs, tandis que les secteurs avec plus de 100 pieds de dépôts meubles pourraient subir une amplification des accélérations trois fois plus forte à une période de 1 s. Les déplacements dus à un séisme varieraient de façon notable sur le territoire. Les spectres de conception définis dans les récents codes du bâtiment de Boston sont conservateurs lorsque comparés aux spectres de réponse calculés en considérant un séisme riche en hautes fréquences. Toutefois, ces codes fournissent une protection inadéquate si le séisme considéré possède une énergie significative aux basses fréquences. Le contenu fréquentiel des séismes de l'Est de l'Amérique du Nord doit être bien caractérisé pour effectuer un microzonage qui soit convenable pour la région.

1. INTRODUCTION

Northeastern North America is a region of moderate earthquake activity that has experienced several significant earthquakes throughout historic times (Ebel and Kafka 1991; Adams and Basham 1991). Strong earthquakes do not occur as frequently in this region as they do along the west coast of North America, but strong ground motions in eastern North America attenuate less with distance than for many other parts of the world including western North America (Bakun and McGarr 2002). Also, there is an older building stock in the cities of eastern North America, and many of these older buildings may have inadequate resistance to earthquake ground motions. Thus, while the occurrence of a strong earthquake in eastern North America is a relatively low probability event, there can be widespread major consequences if such an earthquake does take place.

Many of the cities of northeastern North America are located at least in part on soft soils such as river floodplain deposits, coastal muds, or estuarine sediments. Furthermore, the land area of cities like Boston, New York and Montreal have been expanded by the creation of man-made filled land. A problem arises because the soils in these cities can modify and often amplify earthquake shaking relative to that of nearby bedrock sites. Seismic microzonation studies are used to define those sections of an urban area that may experience earthquake ground shaking amplification, liquefaction, and other seismic amplification effects. Microzonation studies make use of detailed spatial maps of the geologic and geotechnical properties of the soils throughout an urban area. Until recently, the compilation of geological and geotechnical maps was carried out by hand. Today, geographic information system (GIS) software and computer databases make the storage, manipulation, display and update of map-based data easy and efficient. Furthermore, GIS databases can be interrogated to get input data for carrying out analyses of the spatial distribution of ground shaking amplification or liquefaction potential, which an investigator can use to study variations in the spatial ground shaking patterns for different earthquake scenarios (Ebel et al. 2003).

This paper summarizes a GIS-based microzonation analysis of Boston, Massachusetts and uses the results of that analysis to compare the expected earthquake ground motions in Boston to those defined in some representative building codes. The GIS database is comprised of maps and descriptions of Boston's surficial geology, along with soil profiles and geotechnical properties. The database also contains derived results estimating the expected spatial variations in earthquake ground motions at different periods of shaking. Information from independent studies that contain corroborating data and analyses are also included in the GIS database. Methodologies similar to those used in this study can be applied to any urban area.

2. SURFICIAL GEOLOGY AND GEOTECHNICAL PROPERTIES OF BOSTON SOILS

2.1 Surficial Geology of Boston

Boston, Massachusetts was built on what was once the small, hilly Shawmut peninsula with the Charles River estuary to the west and Boston Harbor to the east. The peninsula was a good site for the first English settlers, but its small land area and steep hills became an impediment to the growth of the city. Filling areas along the Boston waterfront to create more city surface began in the 18th century and was pursued vigorously during the 19th and early 20th centuries (Woodhouse et al. 1991). During this time period the hills were removed and dumped into the surrounding tidal flats, approximately tripling the original city surface and creating modern Boston. Figure 1 shows the original and modern shorelines of downtown Boston.

The history and current distribution of the surficial geology of Boston is presented in great detail by Woodhouse et al. (1991) and Skehan (2001). The surficial materials above the bedrock have been laid down subsequent to the continental glacial that covered the Boston area until about 15,000 years ago, when the ice rapidly retreated to the north. The bedrock, made up of Cambridge argillite, became littered with an irregular covering of tills and sands in geologic formations like drumlins, end moraines, eskers, and outwash deposits. The rapid melting of the glacier left the Boston area in a topographic depression created by the weight of the continental ice, causing the sea to extend far inland relative to its current shoreline. In the Boston area marine clays were deposited upon the glacial materials during this time of local inundation. By 10,000 years ago global sea level had dropped significantly, bringing the low-lying land in Boston above sea level and desiccating the clays. Subsequently, local sea level steadily rose until it approximately reached its current position about 3,000 years ago.

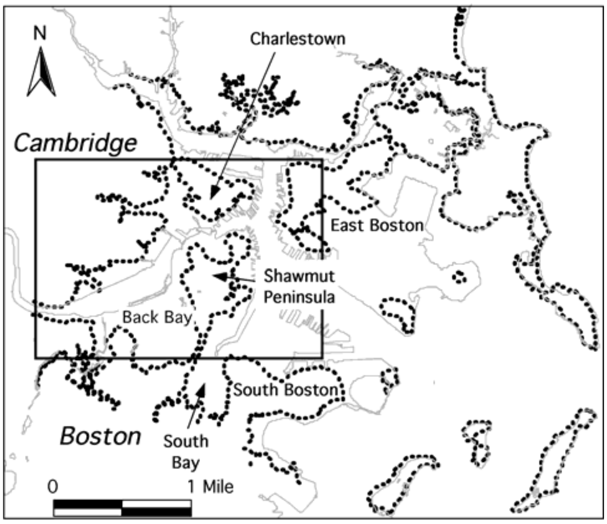

Figure 1. Map of downtown Boston and vicinity showing the modern shorelines (light gray lines) and the original shorelines (bold dotted lines). The locations of those sections of Boston discussed in the text are also shown. The box shows the area within which the microzonation analysis was carried out.

Today there is an irregular bedrock surface under Boston and surrounding towns. In many places surrounding Boston, the bedrock is exposed at the surface, while in Boston itself the bedrock lies anywhere from a few feet to as much as almost 300 feet below the modern surface. Stratigraphically above the bedrock there is a layer of till and outwash deposits, on top of which are marine sedimentary layers. The marine sediments above the till typically are a series of clay layers (including the locally well-known Boston blue clay), and in many places these are overlain by sands and silts. The highest natural layer is normally a few meters of organic-rich silt. In many places the surface today is comprised of landfill of mixed materials from nearby areas.

The distribution of surficial soils in Boston and the variable bedrock depth has directly affected the foundation systems for structures in the Boston area. Where possible, buildings are founded on bedrock or the till layer, while where this is impractical, the buildings are usually founded on piles driven into well consolidated clay layers. Because the depth to the bedrock and till varies even over distances of hundreds of meters, building foundation conditions can be quite different in different parts of the city.

2.2 Geotechnical Properties of Boston Soils

For our Boston microzonation analysis, data on the subsurface lithology and geotechnical properties were acquired from many engineering boring logs for the area as well as from some geological surveys. The most detailed subsurface information was obtained from downhole and crosshole geophysical and geotechnical investigations conducted for the Central Artery/Third Harbor Tunnel (CA/T) project, which began in the late 1980s. A number of geotechnical, geophysical and laboratory measurements were acquired for several sites along the CA/T route. These data were included in our GIS database along with several hundred older borehole measurements that were taken throughout the greater Boston area (BSCES 1961, 1969, 1970, 1971 and 1980). Some of the older borehole logs give soil type and blowcount variations with depth, while others, particularly those from the first half of the twentieth century, sometimes contain little more than generalized descriptions of downhole lithologies. The available borehole data provide a rather irregular coverage of the study area. A subset of the borehole dataset that provides an approximately uniform coverage for the study area was included in the microzonation analysis.

The GIS database (Britton 2003) consists of a large number of information layers. The primary GIS layers contain the location of each borehole from which data were included, lithologic and geotechnical information for each borehole, maps of the modern and original shorelines of Boston, a map of the surficial geology (Kaye 1978), interpreted cross-sections of the surficial geology of Boston (Hawkes 1987) and maps of the roadways in the area. Other information layers necessary for the microzonation analysis were derived from these primary data. For example, a GIS layer showing depth to bedrock for the entire study area was constructed and then interpolated using a kriging method to estimate the bedrock depth at any point between the boreholes. Some other GIS layers derived from the primary data were the depth to each lithologic layer and the thickness of each lithologic layer. Kriging was also used to extrapolate these layers throughout the study area.

Geotechnical soil engineering and index properties, such as shear wave velocity, shear modulus, Atterberg limits and unit weight, are necessary for computing the expected surface ground motions from bedrock earthquake motions. Since these properties have been measured directly at only a few localities in the study area (primarily as part of the CA/T project), it was necessary for each layer in this study to make a correlation between each soil type and the average value of each soil property (Wysockey 1990). For those boreholes where soil properties had not been measured directly, the average shear-wave velocity for each soil layer was estimated from blowcount information. The estimated soil properties throughout the region were then kriged and mapped into the GIS database. For example, Table 1 lists the average low-strain shear-wave velocity for each soil layer in the Boston area from this analysis.

Earlier microzonation maps and studies for Boston were also included in the GIS database. Those maps and studies are Crosby (1932), Haley & Aldrich (1983), Wysockey (1990) and Taylor (1992).

Table 1. Average Shear-Wave Velocities for Boston Soil Layers

Geologic Unit	Shear-Wave Velocity fps
Fill	450
Organics	350
Outwash Deposits	500
Marine Clay	750
Outwash Deposits	1150
Glacial Till	1750
Bedrock	2500-4500

Note: Average velocity values determined for CA/T crosshole and laboratory measurements (from Britton 2003).

3. POTENTIAL GROUND SHAKING IN BOSTON DUE TO FUTURE EARTHQUAKES

3.1 Microzonation Maps

As part of the analysis of Britton (2003), maps of the estimated surface ground shaking were created for two different earthquake scenarios. These estimated ground-shaking maps were created using the data layers of the GIS database. First, a regular grid of points covering the analysis area was selected. At each grid point a 1-D profile of the soil types and properties were extracted from the database. The profiles were then used to perform a 1-D soil response analysis using computer codes such as SHAKE (Schnabel et al. 1972), UFSHAKE and WEBSHAKE (Urzua 2004) to compute the estimated surface ground motions. The two earthquake ground-motion records used as the input rock ground motions are the synthetic ground motion that was used in the design of the CA/T project and an observed ground-motion record from the Valparaiso, Chile earthquake of 1985. The CA/T record is rich in high-frequency energy, with a response spectrum similar to that for the 1988 Saguenay, Quebec earthquake. The Valparaiso, Chile earthquake record is relatively rich in lower frequency energy and was used to study the possible effects in Boston of a low frequency earthquake source. Maps of PGA and pseudospectral ground motions at periods of 0.3 sec and 1.0 sec were constructed for the study area for each earthquake, and these maps were also entered into the GIS database (Britton 2003; Ebel et al. 2003).

The ground-motion microzonation maps for the two input earthquakes indicate the spatial variations of expected ground motions throughout Boston. Maps of ground-motion amplification (the ratio of the estimated ground motion on the soil surface relative to input ground motion representative of a surface bedrock site) were created and included in the GIS database. As an example, the map for the 5%-damped spectral accelerations at a period of 1.0 sec from the CA/T earthquake (Figure 2) shows that the earthquake ground motions would be amplified by a factor of 2 to 3 in the Back Bay relative to bedrock sites. Cambridge and east Boston would experience little or no amplification at this period of ground motion. At the same time, the PGA maps generated for this scenario earthquake show that areas of east Boston and Cambridge would likely experience greater surface peak accelerations than for bedrock sites, while the surface PGA motions in the Back Bay would be deamplified relative to the bedrock ground shaking. Thus, the amount of modification of surface ground shaking in Boston relative to that of the bedrock is a strong function of the period of that ground shaking, as expected.

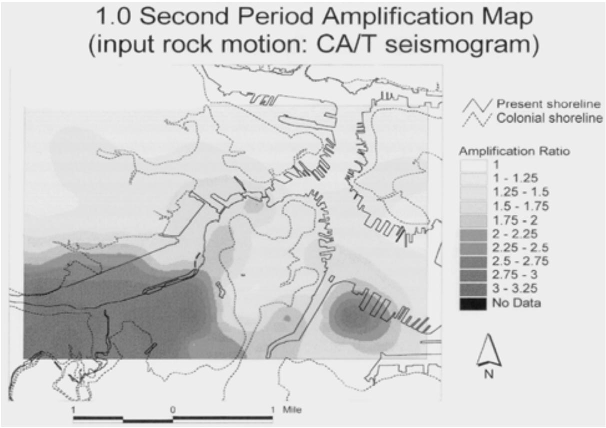

Figure 2. Map of the amplification of the 5%-damped spectral acceleration at 1.0 sec period for the CA/T earthquake with a PGA of .11g in downtown Boston and vicinity (from Britton 2003).

3.2 Calculated Versus Code Response Spectra

While ground-motion amplification maps, such as that in Figure 2, are a useful guide for predicting what parts of the Boston area might experience the strongest shaking in future earthquakes, it is the acceleration response spectra that are the most important consideration if structures are to be built to withstand future earthquakes. In this study we have chosen to quantify the anticipated level-ground response spectra of future earthquakes in Boston by using uniform hazard spectral shapes for 5% damping constructed in the manner outlined by BSSC (1997) for the U.S. National Earthquake Hazards Reduction Program. These response spectral shapes are characterized by a constant spectra acceleration at short periods and a spectral shape that decays as the reciprocal of the period (i.e., T^{-1}) of the ground motion period at longer periods.

Different types of manmade structures have different engineering design criteria, and therefore their design is specified by different seismic design codes. Figure 3 shows the design elastic response spectra for buildings from the Massachusetts State Building Code (MSBC 1997) and from the 1997 NEHRP design provisions (BSSC 1997) as well as for highway bridges from the AASHTO design provisions (AASHTO 2002). For all sets of code provisions, the design response spectra for the soil site classes with the highest expected ground-motion amplification are shown. Clearly, the AASHTO design spectra are the most conservative at both shorter and longer periods. The NEHRP design spectra reflect the high-frequency excitation that has been found for many earthquakes in eastern North America (e.g., Atkinson 1993). These design spectra are much greater at short periods (0.3 s and less) but less at longer periods than the Massachusetts State Building Code, which has a shape that was determined in the 1970's before modern data on earthquake sources in eastern North America had become available.

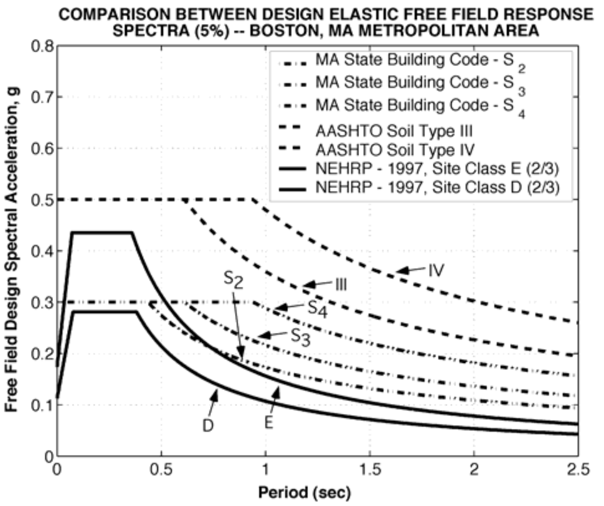

Figure 3. Design elastic freefield response spectra for 5% damping for highway bridges (AASHTO) and buildings (NEHRP and MA State Building Code) for soft soil classes for Boston, Massachusetts.

One important goal in the present study is to assess what kinds of earthquake response spectra might be observed in different parts of Boston in future strong earthquakes. Therefore, we selected for detailed analyses a number of different sites in Boston (Table 2) that had undergone extensive geotechnical investigations as part of the CA/T project, and so the soils under these sites are particularly well-characterized. One analysis was to determine how these sites might respond to the occurrence of an earthquake with a bedrock ground motion like that of the CA/T event. For each site we found the site-specific ground-motion amplification factors for the CA/T earthquake input from the Britton (2003) ground-motion amplification maps (such as that in Figure 2) and applied these amplification factors (instead of the NEHRP Fa and Fv factors) to the 0.2 s and 1.0 s 5%-damped spectral response values from the 2002 U.S. Geological Survey National Seismic Hazard Maps with a 2% chance of exceedence in 50 years. We then followed the BSSC (1997) method for calculating response spectra, including reducing the final spectral accelerations by a factor of 2/3 as called for in the code. The results of this analysis are shown in Figures 4, along with the 1997 NEHRP design spectra for soil classes D and E.

Table 2. Boston Soil Sites Analyzed in this Study

Site	General Location	Overburden Thickness (ft)
C1	Charlestown	55
C2	Charlestown	85
C3	Charlestown	60
D1	Cross & Hanover Sts. (Downtown Boston)	56
D2	State & Atlantic Sts. (Downtown Boston)	89
D3	Atlantic & Congress Sts. (Downtown Boston)	83
S1	S. Bay Interchange (N)	153
S2	S. Bay Interchange (S)	89
S3	South Boston	63
H1	Harbor Tunnel	70
E1	East Boston	127

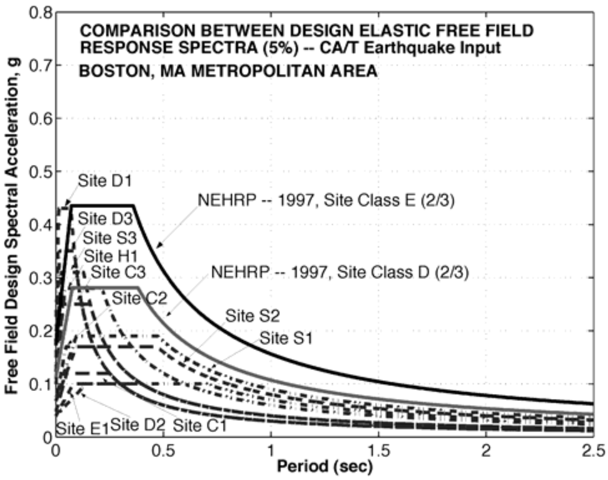

Figure 4. Calculated response spectra for 5% damping for a number of soils sites in Boston, Massachusetts (the sites are listed in Table 2) along with the NEHRP design spectra for Boston computed for soil classes D and E.

Figure 4 shows that the response spectra calculated in this study for the Boston soil profiles using the CA/T earthquake as the bedrock input earthquake have lower values than the NEHRP design spectra for soil classes D and E at periods of engineering interest. The low spectral response values at periods longer than 0.3 s of the response spectral acceleration calculated for the Boston sites in Figure 4 is controlled by the spectral shape of the CA/T earthquake and by the amount of amplification in the Britton (2003) maps that were computed using the CA/T earthquake. The CA/T earthquake, like the 1988 Saguenay, Quebec earthquake upon which it is based, has very little energy at periods longer than about 0.3 s, and this influences the amount of amplification at longer periods due to the local soils.

An earthquake that is richer in long-period energy (above 0.3 s) will have greater ground motions in the Boston area than those shown in Figure 4. To quantify how much the frequency of the earthquake ground motions influences the site-specific ground motions in Boston, the analysis shown in Figure 4 was repeated with the strong-motion record from the 1985 Valparaiso, Chile earthquake used by Britton (2003) and Taylor (1992). This ground motion has a much greater ratio of long-period energy to short-period energy than that of the CA/T earthquake. For this analysis we found the site-specific ground-motion amplification factors for the Valparaiso earthquake input from the Britton (2003) ground-motion amplification maps and once again applied these amplification factors (instead of the NEHRP Fa and Fv factors) to the 0.2 s and 1.0 s 5%-damped spectral response values from the 2002 U.S. Geological Survey National Seismic Hazard Maps with a 2% chance of exceedence in 50 years. We used the BSSC (1997) method to find the response spectra in Figures 5 (including reducing the final acceleration spectra by a factor of 2/3), along with the 1997 NEHRP design spectra for soil classes D and E.

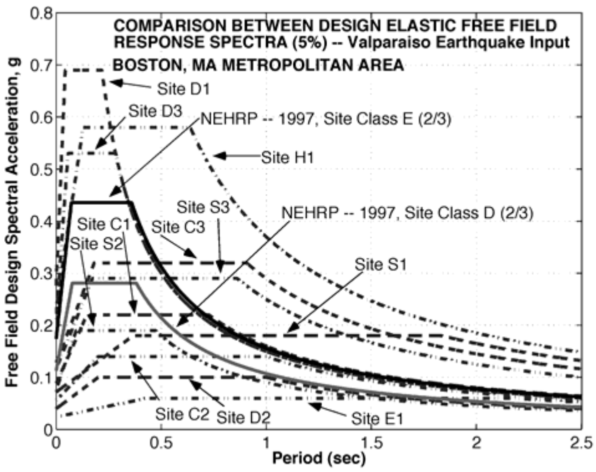

Figure 5. Calculated response spectra for 5% damping for a number of soils sites in Boston, Massachusetts (the sites are listed in Table 2) along with the NEHRP design spectra for Boston computed for soil classes D and E.

The site-specific response spectra in Figure 5 are quite different than those for the same sites in Figure 4. The response spectra for many of the sites in Figure 5 equal or exceed the NEHRP design spectra at some or all periods. This is especially true for periods longer than about 0.5 s, where a number of the sites show spectral values that exceed the code spectra. The differences between Figures 4 and 5 illustrate how strongly the frequency spectrum of the input earthquake can control the results of a microzonation analysis. Ground motion amplification maps, such as the one shown in Figure 2, inherently reflect the frequency content of the earthquake ground motion used to calculate the amount of surface amplification due to the local soil column. Different input earthquakes will give different ground-motion amplification maps for the same area. Recent disagreements concerning the spectral content of earthquakes eastern North America (Atkinson 1993; Haddon 1996; Atkinson et al. 1997; Haddon 1997) must be resolved before definitive ground-motion amplification maps for a city like Boston can be generated and used for site-specific design codes.

4. DISCUSSION AND CONCLUSIONS

Observational evidence from earlier studies confirms that significant variations in earthquake ground motions can be expected throughout the Boston study area. In one study, Ebel and Hart (2001) found site-specific felt reports in newspapers for a number of twentieth century earthquakes that were felt in Boston. They assigned MMI values to each report where possible and then mapped those reports to delineate areas in Boston where the observed MMI reports were greater than those expected based on the earthquake magnitude and its epicentral distance to Boston. Places where enhanced ground shaking was observed were the thick fill area of the Back Bay, Beacon Hill on the original Shawmut peninsula, and South Boston. All of the Ebel and Hart (2001) observations are incorporated in the GIS database of Britton (2003).

Hayles et al. (2001) used field measurements of background microtremors at a number of sites in Boston and Cambridge to determine the major resonant frequencies of the local soils. Their study found soil resonances at periods of .5-1.0 s in the Back Bay, .2-.4 s on Beacon Hill, and .2 s in the South End, all of which correlate with amplification maps of Britton (2003). The Hayles et al. (2001) sites and resonant frequencies are included in the Britton (2003) GIS database.

As expected, one result of this study is that the spectral content of the input earthquake in a microzonation analysis plays a very important role in the determination of how much amplification or deamplification as a function of ground-motion period can take place at different soft soil sites in an urban area like Boston. One way to quantify this observation is to input a large number of different earthquake time series, each with a realistic earthquake frequency spectrum, into the soil profiles for the study area and to compute ground-motion amplification maps for each input earthquake. In this way, expected ground-motion maps for different earthquake source spectra and different earthquake magnitudes can be determined, along with statistical properties of the ground-motion amplification or deamplification from the entire suite of test earthquakes. Different microzonation maps for different possible earthquakes or earthquake source locations might need to be created and considered for design codes.

GIS-based microzonation studies are an effective way to carry out this next level of microzonation analysis. The GIS methodology makes it easy create and analyze many different ground-motion amplification maps, such as those computed using different input earthquakes. GIS codes can also be used to perform statistical analyses of the computed maps. Through this kind of analysis, the spatial distribution of expected ground motions from all possible earthquakes to affect an urban area like Boston can be analyzed and quantified.

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