Award # G14AP00060 and G14AP00061

Near Surface Sediment Model and Site Response for Boston: Collaborative Research with Tufts University and Boston College

Laurie G. Baise
Tufts University
200 College Ave.
Medford, MA 02155
617-627-2211, 617-627-3994, laurie.baise@tufts.edu

John E. Ebel
Weston Observatory
Boston College
381 Concord Rd.
Weston, MA 02493
617-552-8319, ebel@bc.edu

June 1, 2014-August 31, 2015

Abstract:

The City of Boston is located in a shallow sedimentary basin within the fault-bounded Boston Basin. The Boston Basin is defined by north-dipping faults that separate granitic and volcanic rocks from meta-sedimentary rocks. The bedrock is overlain by glacial deposits. In the downtown area and along the two rivers that feed Boston Harbor, the glacial deposits are overlain by marine clay, marsh deposits, and then artificial fill, creating a shallow sedimentary basin. The impedance contrast between the young sediments and the bedrock is on the order of three times stronger than the impedance contrast between sediment and bedrock in other well-studied (in terms of earthquake hazard) urban sedimentary basins such as the San Francisco Bay. This strong impedance contrast at relatively shallow depths will result in high frequency resonant peaks as observed at the Northeastern University Vertical Array during the 2011 Mineral Earthquake. This resonance is particularly important in the eastern US because ground motions tend to be rich in higher frequencies due to low attenuation. Additionally, many CEUS sources have been observed to have large stress drops that result in more high frequency energy than typically seen in WUS events.

Ambient noise studies using H/V measurements to determine the fundamental site period (FSP) can be an inexpensive and efficient method to map site effects for a microzonation study. Ambient noise studies are particularly effective in high impedance contrast environments like Boston, Massachusetts, where the soil depth ranges from 1-80 m and the soil (V_s=200 m/s) overlays hard glacial till or bedrock (V_s =2000-3000 m/s). In this project, ambient noise data were collected from 570 locations in the greater Boston area. Nakamura's technique, taking the ratio of the Fast Fourier Transform (FFT) of horizontal components to vertical component, was applied to determine the fundamental site period (FSP) and amplification ratio. The FSP data were mapped across the region and show a consistent pattern with the local geologic and geomorphologic conditions. The FSP data were then paired with depth to bedrock and V_{s30} drawn from 2403 boring logs and 25 V_S profiles. The depth to bedrock and FSP are highly correlated, as are FSP and V_{S30} measurements. The resulting FSP/V_{S30} correlation is comparable with similar studies from high impedance contrast regions in Canada and Japan. The accuracy of single station ambient noise results were also confirmed with single station and vertical array earthquake spectral ratios. The FSP (~0.74 s) calculated from ambient noise data at the Northeastern University (NEU) Vertical Array site in the Back Bay of Boston where the sediment thickness is 51 m is consistent with the FSP (~0.73 s) calculated for the site using earthquake records from the 2011 Mw 5.8 Mineral, Virginia earthquake. Similarly, the H/V based FSP derived from the 2012 M4.0 Waterboro, Maine earthquake recordings at the MIT Green Building (0.6 s) and the FSP derived from ambient vibration recordings (~0.63 s), collected at a site 150 m away from the MIT Green Building, are consistent. Overall, the outcomes of this study demonstrate that ambient noise studies can be used in high impedance contrast environments to reliably and consistently estimate FSP. The FSP estimates can be paired with additional data such as depth to bedrock, V_{S30} estimates, and recorded ground-motion data, to characterize regional site effects.

Introduction

To predict and mitigate the effects of future earthquakes in urban regions, we need to understand the amplification effects due to local and regional variations in surficial sediments and bedrock geology. On the west coast of the United States, urban regions (i.e., Los Angeles, San Francisco, Seattle) have been extensively studied to understand the causes and spatial distribution of amplification of earthquake shaking due to laterally varying soil and bedrock properties. Unfortunately due to the relatively limited focus on seismic hazard, similar investigations for urban regions on the east coast of the United States have been comparatively few (i.e., confined to Memphis and St. Louis). Recent moderate earthquakes in the Central and Eastern United States (CEUS) such as 2011 Mw 5.8 Mineral, Virginia earthquake have brought attention to the potential earthquake risk to cities in moderate seismicity regions, especially for the high-population density eastern seaboard.

Boston, Massachusetts is a prime example of an urban region exposed to moderate seismicity with heightened risk due to the high population density, vulnerability of the historic unreinforced masonry buildings, shallow saturated young coastal sediments, a strong rock/sediment impedance contrast, and low seismic-wave attenuation in the crust. The New England region has a long history of earthquake activity going back to earliest colonial times, and it has experienced strong, damaging earthquakes on several occasions, most notably in 1638, 1727, and 1755 (e.g., Coffman et al., 1982). The earthquake hazard is most clearly illustrated by the 1755 Cape Ann earthquake, which had a magnitude of ~6.0 - 6.2 (Ebel, 2006). This earthquake did significant damage to masonry structures in Boston; Ebel (2006) estimated peak ground accelerations (PGA) to be in the range of ~0.08 to 0.11g, which corresponds approximately to the 5% in 50 yr ground motion on the 2008 USGS National Seismic Hazard maps. A recurrence today of the 1755 earthquake would lead to several billion dollars of damage just within the city limits of Boston, with additional damage in the surrounding suburbs (based on a 1996 HAZUS study for the City of Boston). Much of this projected damage is due to the many old unreinforced masonry buildings in Boston and its suburbs. A 2012 study that included a M6.5 earthquake offshore east of Cape Ann derived a total estimate of damage to buildings in New England at $2.6 billion, with much of that damage occurring in the greater Boston area (Wong et al., 2012). Furthermore, Boston is not the only city in the northeastern U.S. with a demonstrated seismic hazard from historical seismicity. For example, damaging earthquakes also affected New York City in 1737 and 1884 (Sykes et al., 2008) and the recent 2011 Mineral, VA earthquake caused damage in Washington, D.C. where the epicentral distance was 135 km.

In order to evaluate site effects, regional studies can rely on a variety of data sources (e.g., soil borings for stratigraphy and soil properties, geology, ground motion recordings, shear-wave velocity measurements, and dynamic soil properties). Some of these data sources such as soil borings are plentiful in most urban regions, although the challenge lies in assembling them into a common database or geographic information system (GIS). Other data sources such as shear-wave (V_S) measurements are relatively scarce in most urban regions and are expensive to collect. The key to assessment of soil amplification and site effects in a regional context is to determine 1) how to pool and take advantage of multiple sources of data and 2) how to supplement the available data with additional low-cost data to improve the spatial coverage of measurements of soil amplification and site effects. In Boston, we have assembled 2403 soil borings with depth to bedrock information, 25 V_{S30} profiles, ground-motion records at 2 surface stations and 1 downhole array, surficial geology, history of artificial fill, and 570 estimates of FSP from ambient vibration data.

The greater Boston area is well studied both geologically and geotechnically (Mitchell, 1956; Ladd and Edgers, 1972; Trudeau et al., 1974; Kaye, 1979; Kaye, 1982; Johnson, 1989; Swan and Greene, 1998). Under the leadership of Boston Society of Civil Engineers thousands of borehole data beginning from the 1930s were published in catalogs (BSCE, 1931, 1949, 1950, 1951, 1953, 1954, 1956, 1969, 1970, 1971, 1984). Since then, thousands of records have been added to the dataset, which is available for public use. This unique dataset provides excellent spatial coverage of the Boston area in terms of subsurface conditions. The downtown area has been extensively filled, resulting in a layer of miscellaneous fill overlying organic materials, marine clays and glacial till (Johnson, 1989). Downtown Boston was originally a peninsula which is bounded to the North by the Charles River and on the east and south by Boston Harbor. Cambridge, another urban city, is bounded by the Charles River to the south and the Mystic River to the north. In this urban region, which includes these two major river outlets (Charles and Mystic Rivers) and a significant amount of artificially filled land along the river channels and the coast, the natural soil conditions are comprised primarily of marine sediments (organics, sands, and clays). The site effects are dominated by the impedance contrast at the soil/rock interface (Baise et al., 2015; Thompson et al., 2013). The soil sediments have typical shear-wave velocities around 200 m/s whereas the bedrock approaches 2000-3000 m/s (Thompson et al., 2014). Beyond the river outlets, the city has been heavily glaciated and is surrounded by shallow soils over glacial deposits, glacial drumlins, and bedrock.

The ratio of the Fourier amplitude spectra of horizontal components to vertical component (H/V) of ambient noise data at a single station is one of the cheapest and most convenient ways of estimating site effects. This method which utilizes the H/V spectral ratio of ambient noise was first introduced by Nakamura (1989) to estimate the predominant frequency and amplification factor. The Site Effects Assessment using Ambient Excitations (SESAME, 2004) research project also confirmed that the two horizontal components are amplified relative to the vertical component at the fundamental site period. It is also reported that, although the existence of a clear peak can be considered to be an indication of a high impedance contrast at the soil-rock interface, there is no correlation between H/V peak amplitude and actual amplification values (SESAME, 2004). An earlier study in Boston (Hayles et al., 2001) demonstrated that H/V ratios are an effective method for estimating FSP. Bodin et al. (2001) and others have also shown that microtremor H/V measurements accurately identify sediment thickness in the Mississippi River embayment where the sediment/rock boundary has a strong impedance contrast. Although the unconsolidated sedimentary layer in Boston is significantly shallower than in the Mississippi embayment, the same argument applies: strong impedance contrasts lead to clear sediment resonance.

The SESAME (2004) research project recommends the use of H/V technique in areas of low and moderate seismicity due to the lack of significant earthquake recordings as compared to high seismicity areas. The H/V technique is emphasized to be the most effective in estimating the natural frequency of soft soil sites when there is a large impedance contrast with the underlying bedrock (SESAME, 2004). The SESAME project found that the FSP is very close (i.e., less than 5% different) to the fundamental resonance frequency for S waves only if the S-wave impedance contrast exceeds a value of 4 (SESAME, 2004). Given the typical sediment and bedrock velocities in Boston, the impedance contrast is on the order of 10 times and therefore is appropriate for H/V ambient noise estimates of FSP.

Given the assembled dataset, the need for additional constraints on site effects across the region, and the prior success of ambient noise H/V estimates to constrain the FSP in Boston, we collected ambient noise measurements at 570 locations in greater Boston area. We develop quantitative relationships between FSP, surficial geology conditions, depth to bedrock and V_{S30} for our dataset which can be used to predict depth to bedrock and V_{S30} at uncharacterized sites. In addition, ground-motion records are used to demonstrate a good correlation between predictions made from ambient vibration and earthquake data. The goal of this study is to provide estimates of depth to bedrock and FSP across the region for use in future site effects studies for the region. These regional models can be used to inform regional planning (future HAZUS type studies) or site-specific studies that assess seismic hazard, seismic microzonation, and potential future losses due to earthquakes in the Boston area.

Boston Site Conditions

The surficial geology in Boston is controlled by the glacial history, the evolution of the modern river channels, and the artificial fill history of both the alluvial floodplains and coastal shorelines. In most places, glacial till sits on top of competent bedrock and acts as another stiff layer between loose overlying sediments and stiff underlying bedrock. The thickness of the glacial till also varies rapidly from point to point depending on the underlying bedrock topography. Along the Charles and Mystic Rivers, the bedrock elevation is depressed and the depressions have been filled with marine sediments. The sediments include the well-studied Boston Blue Clay, organic silts, marine sands, and artificial fill.

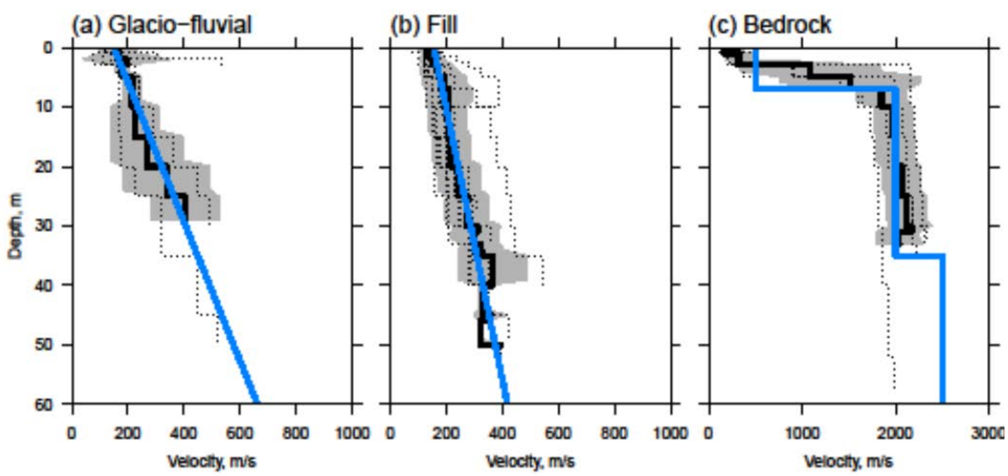

Figure 1. Typical V_S profiles in Boston by surficial geologic unit. The dotted lines show individual Vs profiles, the dark black line shows an average profile for each geologic unit, the gray shows the 95% confidence intervals for each geologic unit, and the blue lines show generic profiles for each geologic unit (from Thompson et al., 2013).

Thompson et al. (2014) estimated V_S profiles at 27 locations in Boston using the Spectral Analysis of Surface Waves (SASW) technique. These V_S profiles are summarized as a function of surficial geology in Figure 1 and indicate that sediment velocities are typically between 200 and 400 m/s whereas near-surface bedrock velocity is on the order of 2000 m/s (Thompson et al. 2013). Using 2403 borings for the region, we were able to constrain bedrock depth throughout the Boston area as shown in Figure 2, with excellent coverage in downtown Boston and along the Charles and Mystic Rivers. We developed a generic soil profile for the region that can be used for regional studies (shown in Figure 2b). Typical bedrock depths range from 12 to 75 m near the Charles River and 24 to 38 m along the Mystic Rivers. The boring database spatial coverage decreases inland and away from downtown Boston.

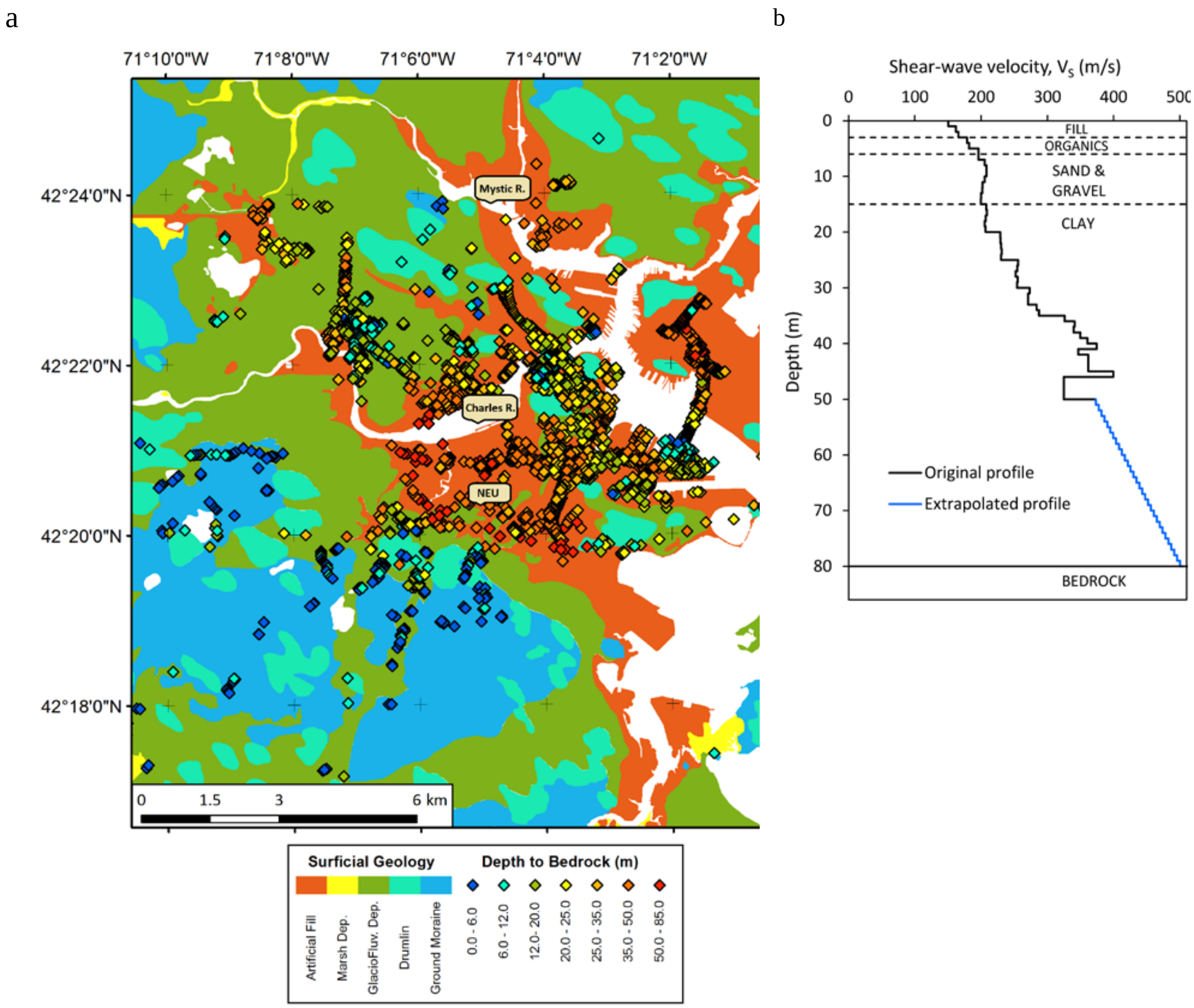

Figure 2. (a) The overlay of depth-to-bedrock data on a surficial geology map of Boston and vicinity. While depth-to-bedrock values are higher along river bends and artificially filled regions, depth to bedrock is lower inland at drumlin and ground moraine sites. (b) Typical soil profile for Boston

A vertical array (NEU) with three-component seismometers has been operated for a number of years at a site close to the Northeastern University Snell Engineering Center (Yegian, 2004). The 2011 Mw 5.8 Mineral, Virginia earthquake was recorded by the NEU seismometers deployed at the ground surface and at 51 m depth. The stratigraphy of this site is given by Yegian (2004) and is typical of a soil site near the Charles River with artificial fill overlying organic soils, marine clays, glacial till and bedrock. The bedrock depth is 51 m at the site with a Boston Blue Clay thickness of 43 m. The 2011 Mineral event was also recorded by a seismometer at 2 km distance from NEU in Jamaica Plain (rock site, V_{S30}=961 m/s, Thompson et al., 2014). In order to demonstrate the effects of local site conditions, the spectral ratio of the surface recordings at NEU and Jamaica Plain is calculated and shown in Figure 3. A 20-point moving average was also applied to smooth the spectral ratio. The results of the analysis show that the amplification between the two sites is approximately 10 times and the fundamental frequency of the NEU site is 1.4 Hz. To check these results, we conducted 1D linear analysis with the NEU stratigraphy and shear-wave velocity by using the 2011 Mineral earthquake recorded at the Jamaica Plain site as the bedrock ground motion. More details of the response analysis of the NEU site are given in Baise et al. (2015). Figure 3 shows that both the earthquake transfer function and the theoretical transfer function result in comparable amplification and consistent FSPs. This result demonstrates the significance of the local site conditions in Boston and the accuracy of the theoretical transfer function analysis.

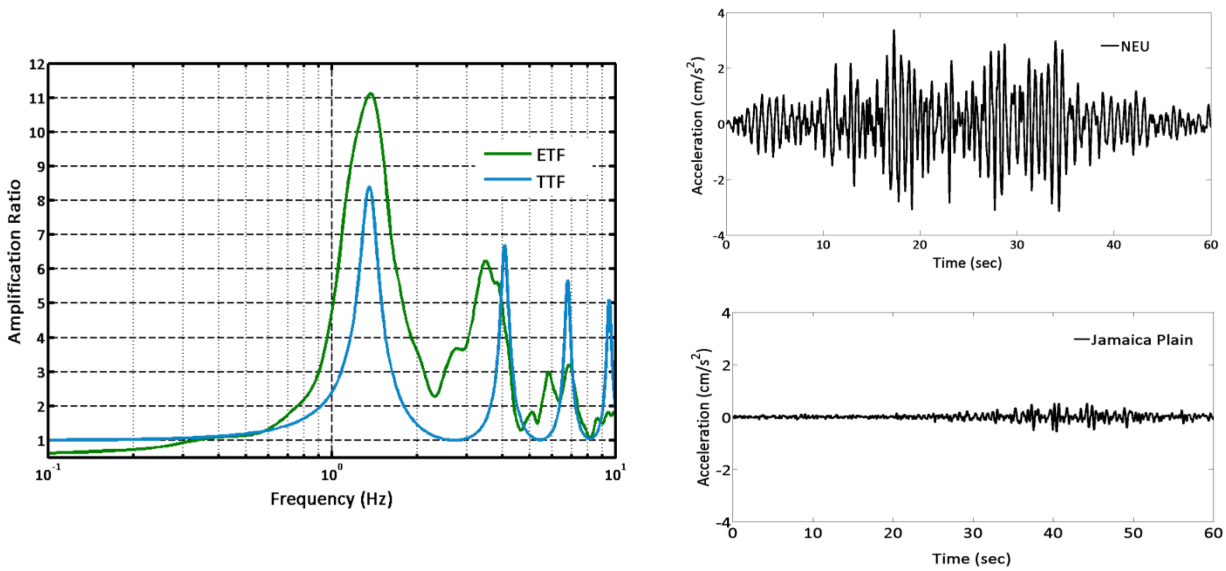

Figure 3. Site amplification at Northeastern University (NEU). The bedrock recordings are from the Jamaica Plain rock site at a distance of 2 km way from the NEU site. The earthquake transfer function is calculated from the field data (green), and the theoretical transfer function (blue) is calculated with the available site information.

Data Collection

Ambient noise data collection and analysis relies on the collection of continuous time series data of ambient vibrations. The instrumentation consisted of a three-component Guralp CMG-40T broadband seismometer and a Reftek RT-130 datalogger. The data were sampled at 100 Hz. From 17 August to 29 December 2014 ambient noise data measurements were collected from 570 locations in the greater Boston area by visiting each site for 15 minutes of data recording.

Figure 4. Picture of the instruments during data collection from one of the sites. Inside the blue box there is a Reftek RT-130 datalogger, to which is connected a three-component Guralp CMG-40T broadband seismometer (to the left of the data logger) and a GPA antenna (below the seismometer in the photo).

Our spatial sampling plan roughly followed a grid with a spacing of about 500 m for even coverage throughout the study area, with locally denser spatial coverage in regions which are known to have artificial fill stratigraphically above Boston Blue Clay. The ambient noise data were collected by two different teams, one each from Tufts University and Boston College. A huddle test was performed with the instruments used in the experiment both prior to and after the data collection phase to insure consistency. The huddle test results showed that the instrument response was consistent over the testing period and for the different sets of instruments used. Because most of the region is densely populated, the data were collected along sidewalks, parking lots and public alleys. These sites also have the advantage of being close to traffic which is the primary noise source. For safety reasons all of the data were collected during daytime. The locations where measurements were made were selected locations to avoid subways and other potentially hollow subsurface locations such as sewage and sanitary lines.

H/V Analysis

We collected 570 ambient noise measurements for use in H/V analysis. The time series were detrended and then the first 120 -180 seconds were removed from the time history to eliminate noise due to the operator turning on and walking away from the instrument (Figure 5-a, b, c). Because of low frequency microseismic energy that is outside our frequency range of interest, we applied a 4^{th} order Butterworth band-pass filter (Butterworth, 1930) as shown in Figure 5-d, e, f. We applied the same filters to all the records with a low-cut frequency of 0.5 Hz and a high-cut frequency of 49 Hz (matching the Nyquist frequency). The low-cut frequency of 0.5 Hz means that we cannot identify any FSP greater than about 2 s. Given the range of sediment thickness in the region and the results of Hayles et al. (2001), the highest FSP that we expect is between 1-1.5 s, and so the low-cut corner was selected to easily pass these periods. After filtering, each record (typically 600-900 s) was divided into 10 non-overlapping windows of data, each data window of 40 seconds length. An FFT was computed for each 40-s data window of each component (Figure 5-g, h, i) and then the 10 amplitude spectra were stacked for each component.

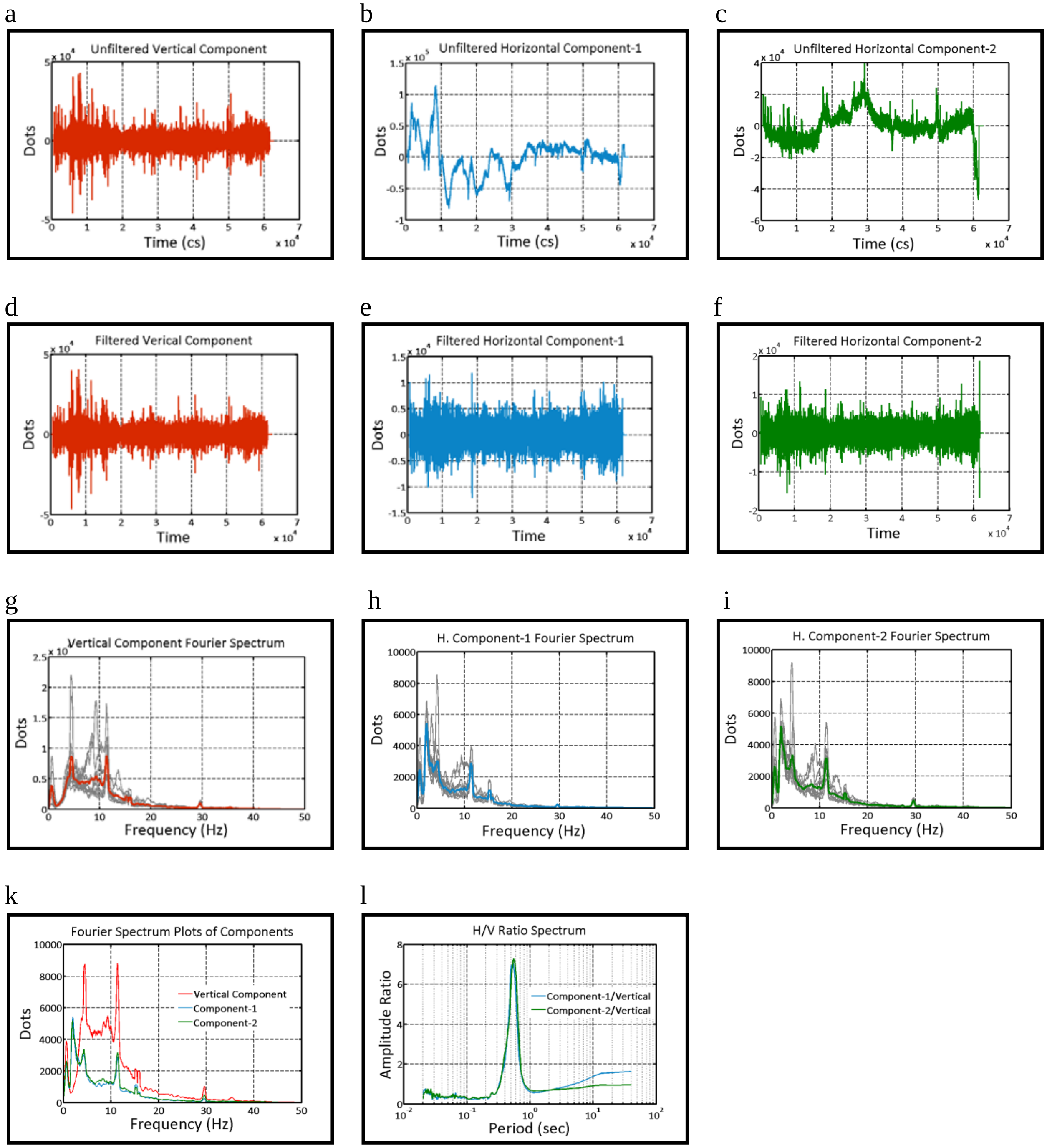

Figure 5. H/V analysis plots for a site having high FSP (a), (b), (c) Unfiltered time histories of the three components of ground motion (d), (e), (f) Filtered time histories of the three components (g), (h), (i), (k), Fourier spectra of the three components (l) Ratios of the Fourier spectra of each horizontal to vertical component.

Using these stacked amplitude spectra, the amplitude spectral ratio H/V (ratio of the horizontal to vertical amplitude spectra) was computed for each of the two horizontal components of motion, and the periods of the spectral peaks were taken. We used a 20-point moving average to smooth the H/V spectral ratios. In most cases, a clear narrow peak with similar periods values was observed in the H/V ratio from each of the horizontal components (Figure 5-k, l). These periods were interpreted to constrain the FSP for the site. From tests of the band-pass filter, small variations in the corner frequencies of the filter did not affect the FSP value, although the changes did impact the magnitudes of the spectral ratio values.

Comparison with the Earthquake Data

Records from the 2011 Mineral earthquake at the NEU vertical array provided an opportunity to further validate the ambient noise results with earthquake recordings. Both the spectral ratios of the horizontal components to the vertical component for the surface seismometer (Figure 6) and for the seismometer at 51 m depth (as previously shown in Figure 3) were determined.

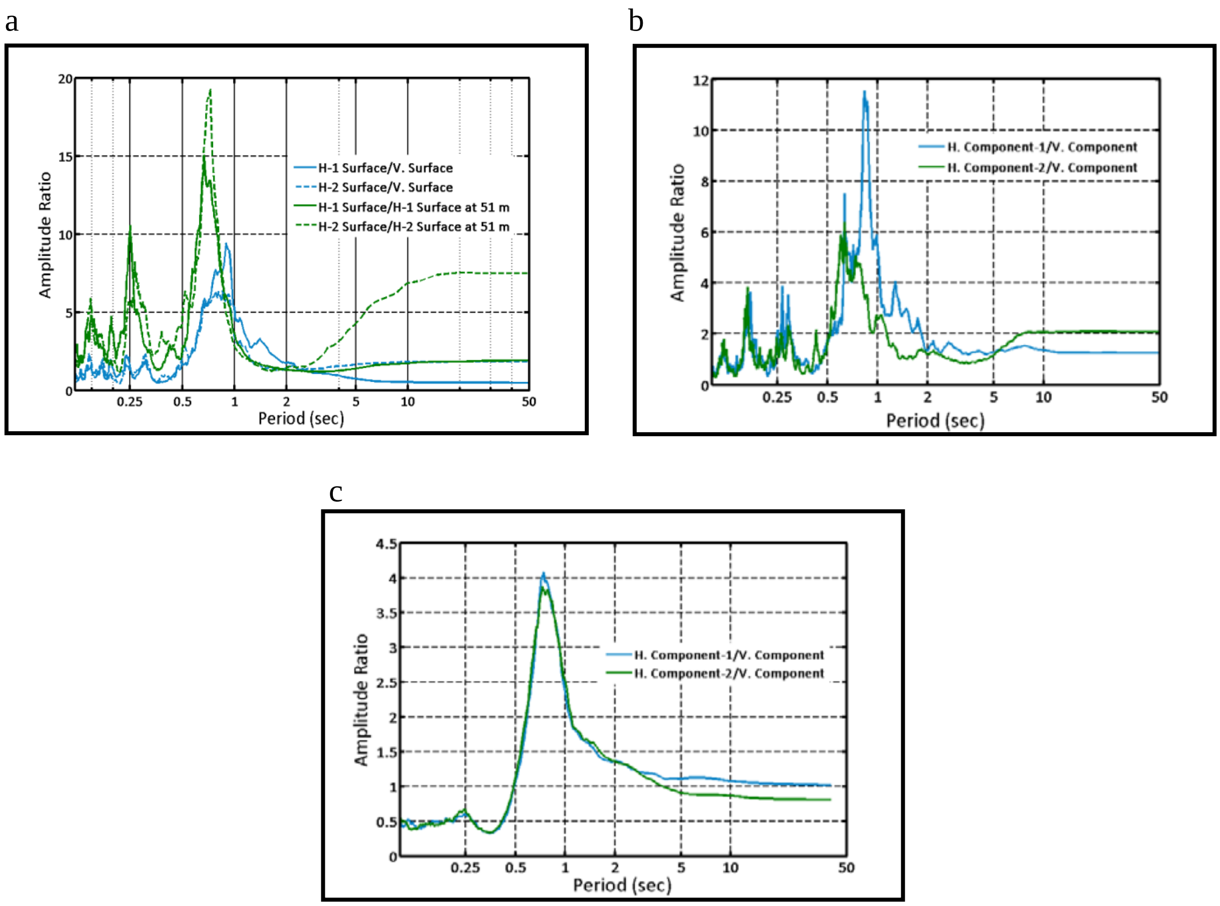

Figure 6. (a) Spectral ratios from the NEU Vertical Array of the 2011 Mineral earthquake showing the H/V spectral ratios of from the surface instrument and from the instrument at 51 m depth. b) H/V spectral ratios of the 2011 Mineral Earthquake at surface at the Snell Building at NEU (c) H/V spectral ratios of ambient noise data from a site nearby to the NEU Vertical Array site.

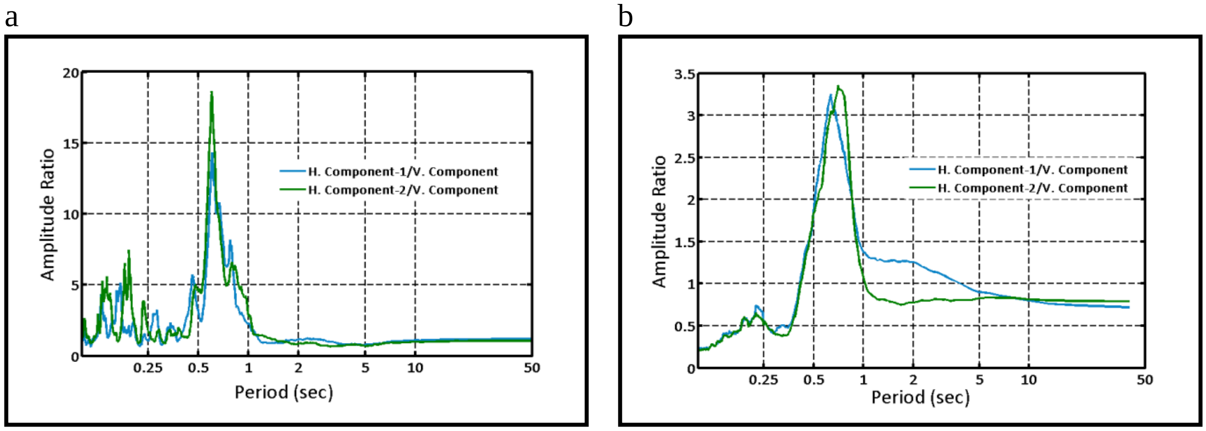

Figure 7. (a) H/V spectral ratios of the recordings of the 2012 Maine earthquake from the basement of the MIT Green Building (b) H/V spectral ratios of ambient noise data from a site to nearby to the MIT Green Building

Figure 6-a shows that the H/V ratios at the surface (0.81 and 0.88 s for the two horizontal components) and the ratios of horizontal components at the surface to the corresponding horizontal components at depth (0.73 s and 0.68 s for the two horizontal components) result in very comparable FSPs. The second peak in the spectral ratios near 0.25 s and 0.27 s in Figure 6-a for the ratios of the surface and depth horizontal components may correspond to S-wave harmonics (SESAME, 2004), although this second spectral ratio peak is not seen in the surface H/V spectral ratios. Within 50 m distance, the 2011 Mw 5.8 Mineral, Virginia earthquake was also recorded by an accelerograph in the basement of the Snell Engineering Center on the NEU campus. The Snell Center is a five story, steel-frame structure on shallow foundations over the same soil profile as that observed for the vertical array site (Yegian, 2004). We conducted the same H/V analysis for this set of records and the results are given in Figure 6-b. FSPs of 0.64 s and 0.82 s are obtained from the analysis of the two horizontal components, which are comparable with the FSPs found at vertical array site. In the H/V ratios from the Snell Center, the smaller spectral peaks at 0.16 s and 0.29 s may correspond to the S-wave harmonics. Finally, we compare the H/V ratios derived from earthquake recordings with the H/V ratios derived from ambient vibration recordings on the NEU campus as shown in Figure 6-c. The ambient noise H/V ratios result in FSPs of 0.74 s and 0.73 s for each component (Figure 6-c). In summary, FSPs at the NEU campus are consistently estimated between 0.64 s to 0.88 s using both earthquake and ambient noise H/V ratios as well as surface/downhole spectral ratios.

To further validate the H/V ambient noise FSP estimates, we used earthquake records from the Green Building on the Massachusetts Institute of Technology's (MIT) Cambridge campus. The October 16, 2012 M4.0 Waterboro, Maine earthquake was recorded by the seismic monitoring system comprised of 36 accelerometers installed in Building 54, also known as the Green Building. The layout of the deployed seismometers and further information can be found in Çelebi et al. (2014). Site conditions at the Green Building are approximately 45 m of sediments including artificial fill and Boston Blue Clay over bedrock. We used the two horizontal components and one vertical component at the basement level to obtain the H/V ratios. The results of the analysis are given in Figure 7-a and show that both of the component ratios resulted in a FSP of 0.60 s with a clear peak. Two secondary peaks are also observed at 0.14 s and 0.19 s, which may indicate potential S-wave harmonics (SESAME, 2004). We also collected ambient vibration data at a site 150 meter away from the MIT Green Building. The results of these analyses are given in Figure 7-b and the FSPs occur at 0.63 s and 0.70 s, indicating that the earthquake and ambient noise FSP estimates are again consistent.

Surficial Geology Comparison

Given the large amount of borehole data available throughout the Boston area, the subsurface conditions in the greater Boston area are fairly well constrained; however, there are significant regions where we have FSP measurements without borehole data. We plot the FSP estimates on a surficial geology map of the Boston area in Figure 8 to show spatial trends in the local site conditions. We use red and orange to signify high FSP values (0.45 to 1.0 s) and blue and green to signify low FSP values (0.02-0.35 s). The yellow shows transitional FSP values (0.35-0.45 s). For the H/V ratio values in Figure 8, we used similar colors to those used for the surficial geology, where red is for artificial fill where we expect deeper sediments and blue and green are for glacial deposits where sediments are expected to be thin. Along the rivers, the geology is generally artificial fill at the surface, whereas the inland surface areas are mostly covered by drumlin, glaciofluvial, and ground moraine. Outcropping bedrock is included in the ground moraine deposit. In Figure 8, a similar pattern can be observed between the surficial geology and the H/V determined FSPs.

In Figure 9-a, we compare the areas around Back Bay, Cambridgeport, South Boston to historical maps that show locations which were historically covered by water and were filled in the 19th century (Figure 9-a). The observed FSPs in these areas are 0.35 s – 1.05 s (Figure 9-b) and the bedrock depth in these regions ranges from 20-70 m. The same pattern is also observed along the east and north shores of Charlestown, in lower Allston and in Medford and Everett where the Malden River meets the Mystic River (Figure 9-c). We also observe high FSPs between the Mystic Lakes and Fresh Pond which are mapped as glaciofluvial surficial deposits (Figure 9-d). These high FSPs indicate a deeper sediment thickness in this area than is typically observed for the glaciofluvial deposits in the region. Looking inland, the FSPs are lower around and south of Brookline Reservoir and Jamaica Plain (Figure 9-e). The FSPs are as low as 0.03 s on ground moraine deposits, indicating shallow sediments over the hard glacial materials. These very low FSP observations are also found in Roxbury, Brighton and Newton where the surficial geology is characterized as ground moraine and drumlin surficial geology. Around Cambridgeport there are some high FSP measurements mapped as glaciofluvial surficial geology. The FSP results in this area indicate that it is likely that the surficial geology map underestimates the extent of artificial fill or that the glaciofluvial conditions include deeper sediments than is typical of glaciofluvial sediments in the region. One of the most interesting results obtained is from the Chelsea. While the measurements around the Island End River show low FSPs, about 1 km to the north high fundamental periods are observed and further north toward the drumlins low FSPs are again observed. A historical map (e.g., Hales, 1819) reveals that at one time Island End River extended in the north and northeast direction into Chelsea (Figure 9-f). Therefore, these locations most likely have some artificial fill atop thick sediments associated with the flood plain of this local river.

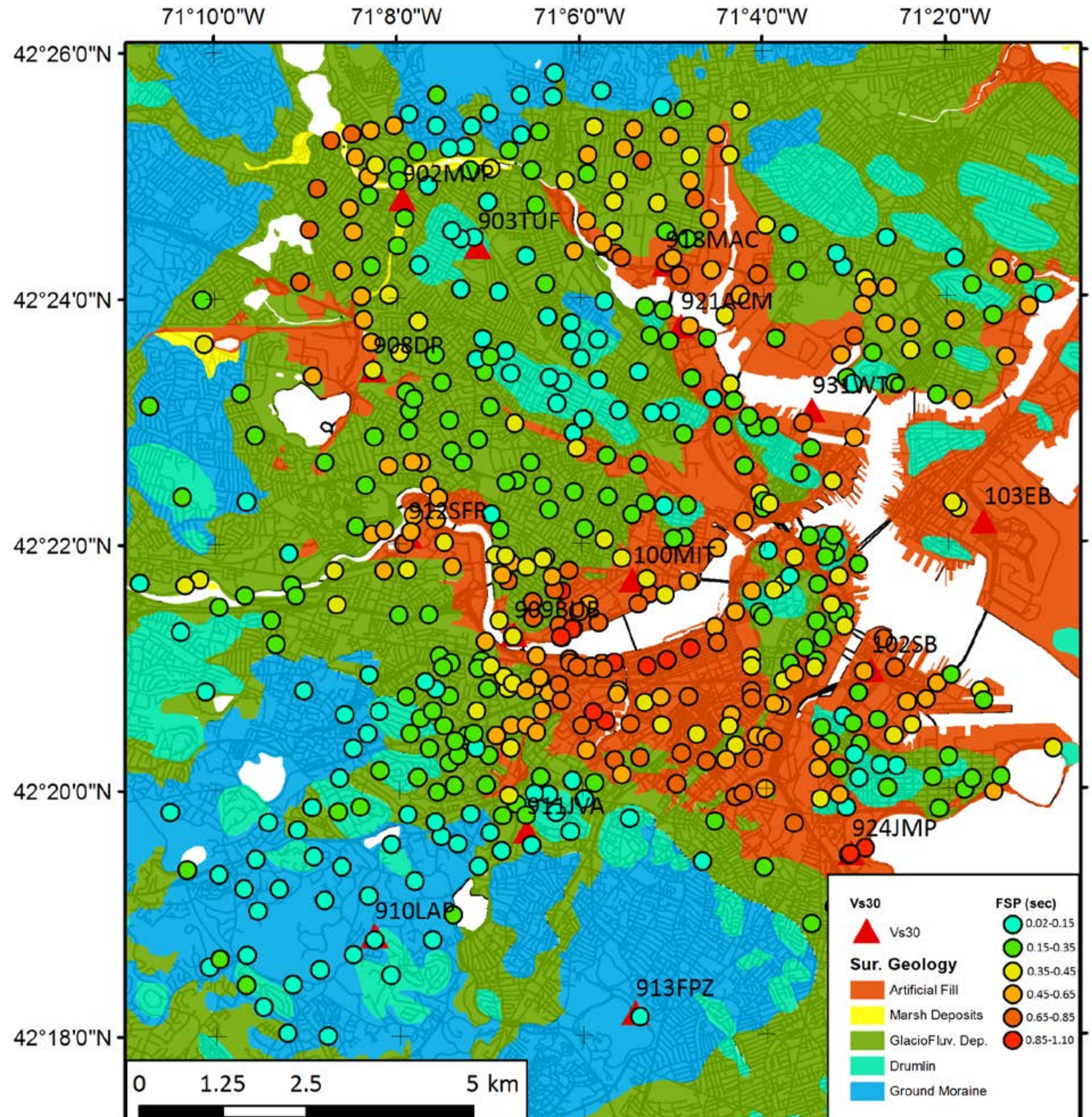

Figure 8. Overlay of FSP determined from H/V ratios on the surficial geology map for Boston (Brankman and Baise, 2008) and vicinity. Areas shown in red are artificial fill locations, green shows the distribution of the glaciofluvial deposits and blue represents the drumlin and till surficial geology conditions.

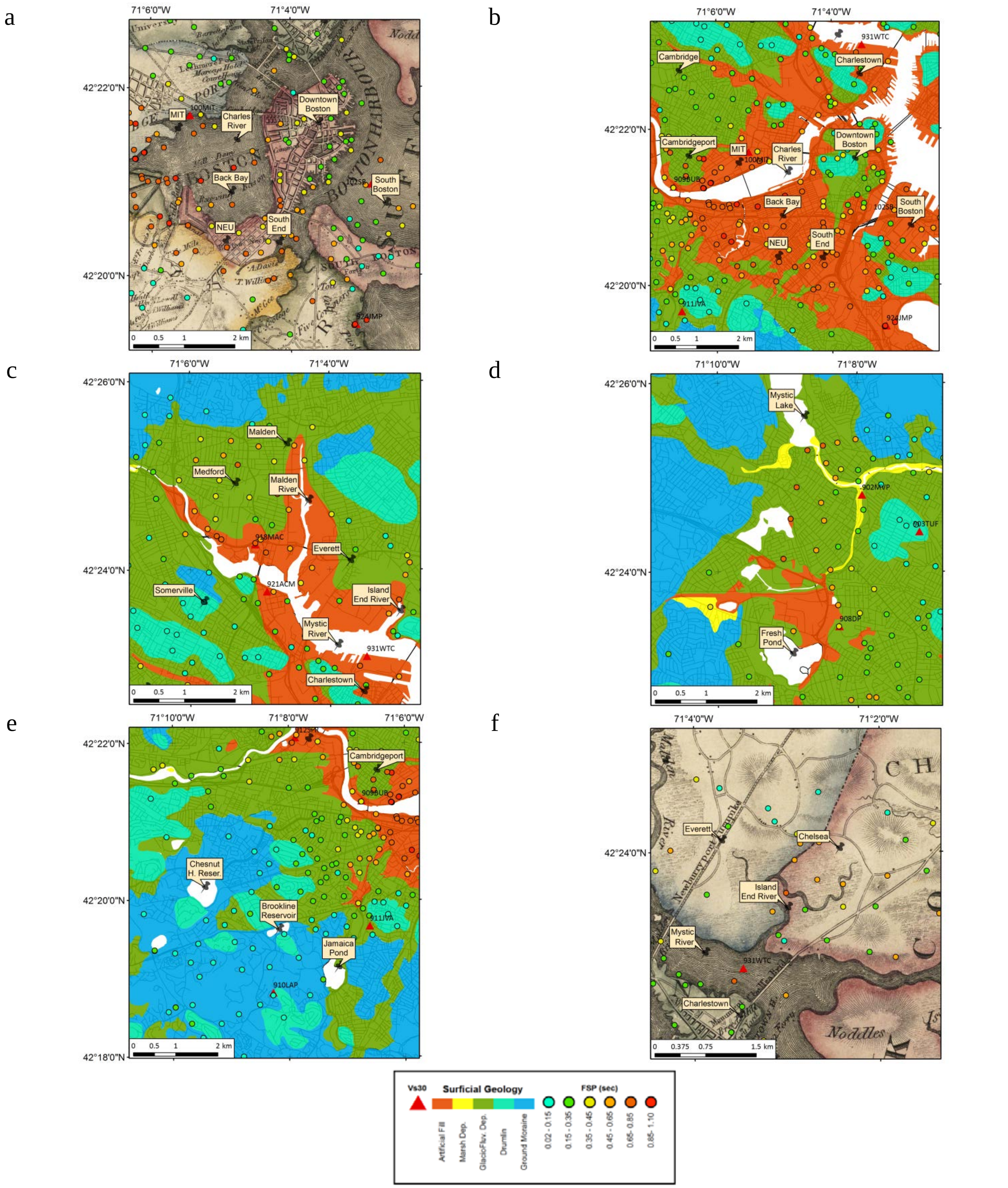

Figure 9. Overlay of FSP from H/V measurements onto surficial geology maps and the 1819 Boston and Its Vicinity Map. (a) Shows the good correlation between the historic map and FSP values for the downtown area. Areas historically that were occupied by water show higher FSP values than land areas. (b), (c) and (e) Display consistency between the surficial geology layers and the FSP values. (d) Observed high FSPs between Mystic Lake and Fresh Pond can be explained by the deeper sediment thickness in this area. (f) Historic east and northeast extension of the Island End River is associated with local relatively higher FSPs.

The FSP dataset is plotted as box plots by surficial geology in Figure 10. Artificial fill and glaciofluvial deposit sites correspond to high and moderate FSPs, respectively, and drumlin and ground moraine sites result in low to very low FSPs. The overlap of the FSP values among the geologic units is relatively low, which means that the surficial geology units can be distinguished from each other by their corresponding FSP mean and confidence interval.

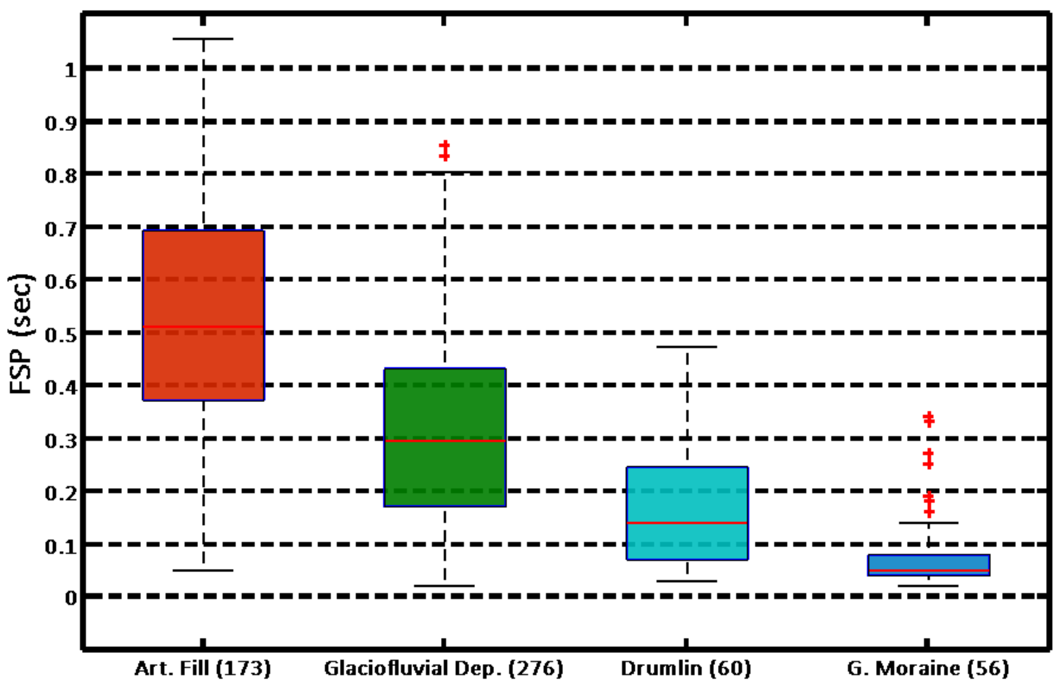

Figure 10. Distribution of FSP as a function of surficial geologic unit in terms of a boxplot

Depth to Bedrock Comparison

We used the extensive soil boring database to build a depth-to-bedrock dataset for the region. For the determination of bedrock depth from the boring-log database, we included only those logs that are clearly identified as rock or bedrock as the lowest unit found in the drill hole. The depth-to-bedrock data are plotted using boxplots by surficial geologic unit in Figure 11. Figure 11 shows that the mean depth to bedrock is smaller when the surficial geology represents harder conditions (drumlin and ground moraine) and larger when the surficial geology represents sediments (artificial fill and glaciofluvial deposits). The depth to bedrock at drumlin sites shows a wide variation while the other surficial geologic units are less variable. During the borehole classification phase we observed a close relationship between rock and glacial till. In general, glacial till overlies bedrock with a thickness of a few meters but sometimes as a thicker layer. The high variability of the depth to bedrock at drumlin sites may be attributed to overlying thick glacial-till layer or misidentification of bedrock due to the hard nature of both layers.

In Figure 12-a, we investigated the relationship between depth to bedrock and the H/V-based FSPs. The borehole records within 250 m distance of an H/V FSP measurement site were matched to the FSP site. Matching was made using a one-to-one basis in that none of the records from either dataset were matched more than once to a record of the other dataset. As a result, 130 FSP measurements were matched with 130 depth-to-bedrock measurements. The linear relationship observed in Figure 12-a and given in Equation (1) indicates that there is high correlation between FSP and the depth to bedrock. Figure 12-b shows the residuals from the best-fit line. In Equation (1) H is the depth to bedrock and p1 and p2 are linear regression constants. The coefficient of determination (R2) in Figure 12-a is found out to be 0.67, suggesting that the data have a linear trend but with a large amount of scatter. The scatter may be attributed to the confounding effect of glacial till or other misidentification of bedrock as discussed above. In addition to this, the scatter may also be attributed to the FSP dataset. The glacial till might create a strong impedance layer that reflects energy prior to the bedrock interface and result in lower FSPs. According to SESAME (2004), under these conditions (two significant impedance contrasts) it is likely to have two different peaks corresponding to different FSPs. However, during our analyses we did not notice two different distinguished peaks in any of the sites. This may either be because the till layer is relatively thin which causes the two peaks to couple as a single peak or because the second impedance contrast is not large enough to trap energy.

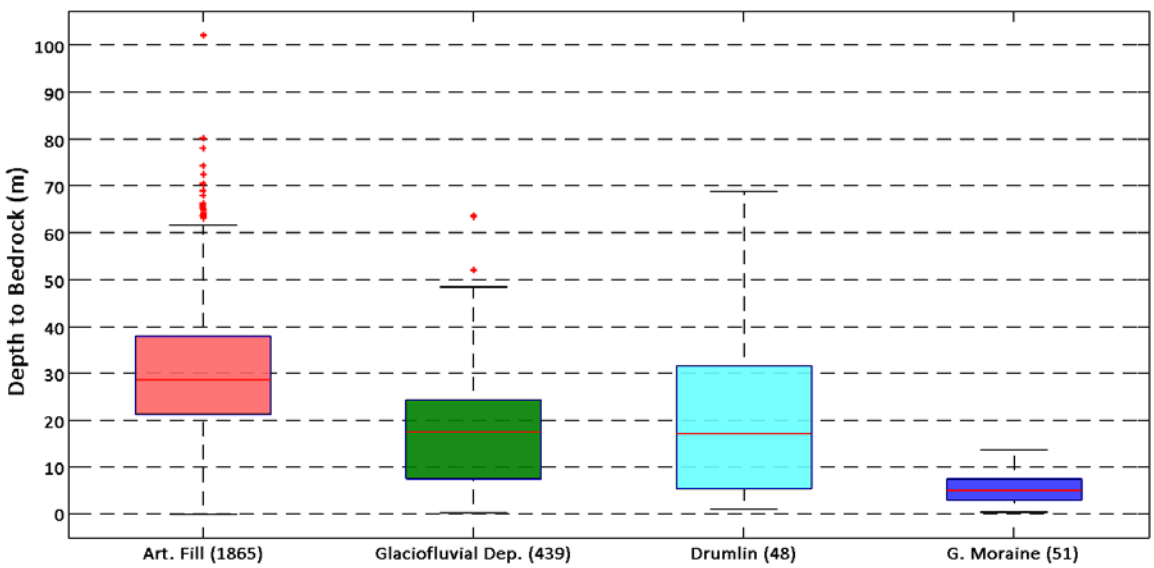

Figure 11. Distributions of depth to bedrock by surficial geologic unit in terms of boxplots. The numbers in parenthesis show the number of data in each surficial geology bin.

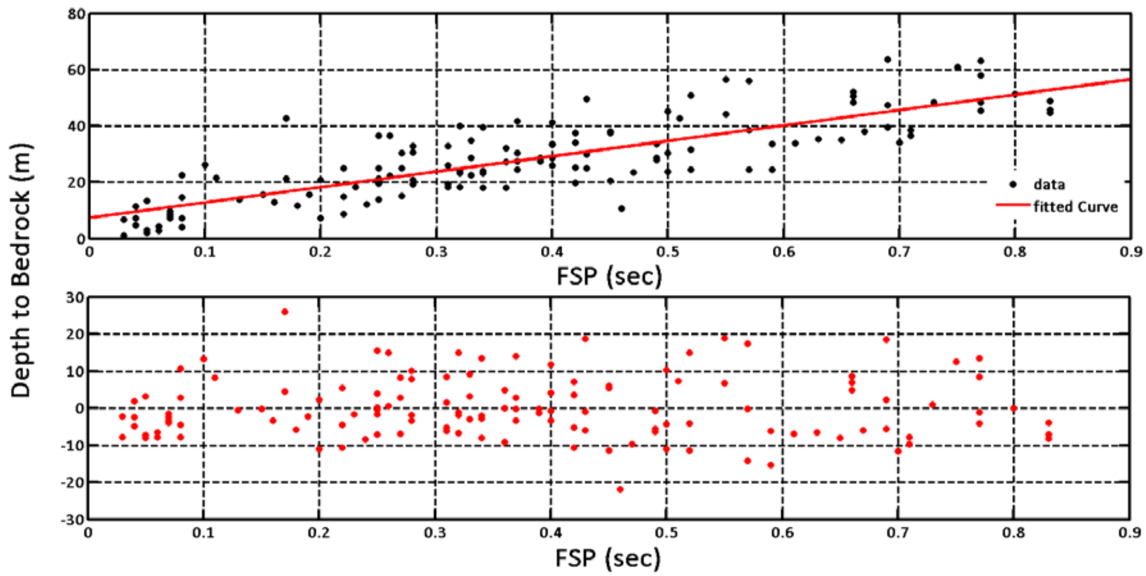

Figure 12. (a) Depth to bedrock and FSP plot (b) Residuals of the field data from the linear trend model.

H = p1*FSP + p2 (1)

Coefficients (with 95% confidence bounds):

p1 = 54.68 (47.95, 61.41)

p2 = 7.47 (4.55, 10.38)

$0.03 \leq \text{FSP} \leq 0.85$

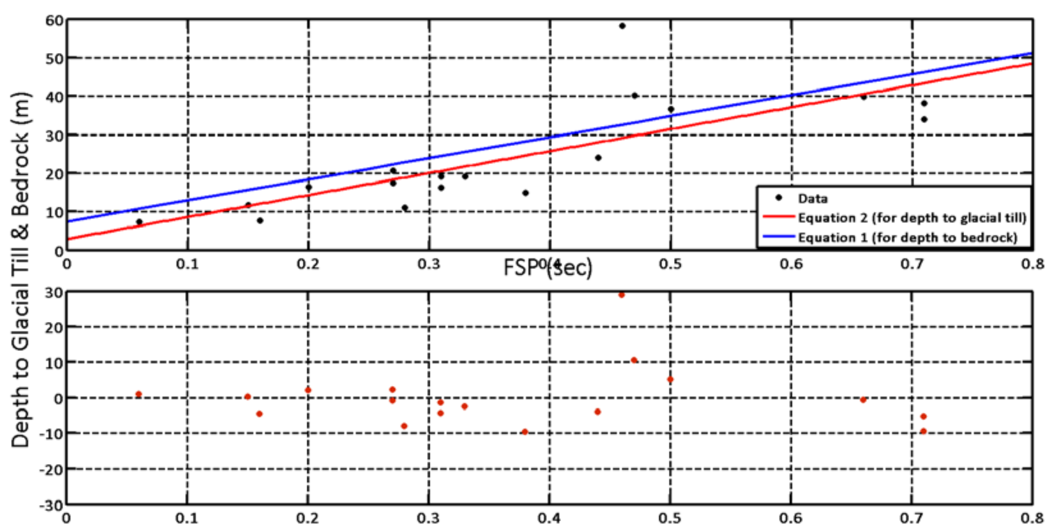

Figure 13. (a) Depth to glacial till and FSP plot. Equation (1) is also plotted to show the difference between equation (1) and equation (2) (b) Residuals of the field data from the linear trend model.

The same procedure in determining equation (1) was applied to the glacial till layers as the lowest layer in borehole to determine the possible effect of glacial till. Figure 13-a and Figure 13-b show a clear correlation between depth to glacial till and FSP.

$$H = p1*FSP + p2 \qquad (2)$$

Coefficients (with 95% confidence bounds):

p1 = 57.01 (32.27, 81.74)

p2 = 2.93 (-7.304, 13.16)

$0.03 \leq FSP \leq 0.85$

The plot of equation (1) and (2) in Figure 13 shows the depth to bedrock is consistently 2-4 m greater than depth to glacial till.

Depth to bedrock

Using the depth to bedrock and FSP correlation developed above, we predicted depth to bedrock at each of the 570 FSP locations. These values are included with depth to bedrock database in Figure 14 to show depth to bedrock across the region. The depth-to-bedrock data can be interpolated to create a continuous surface.

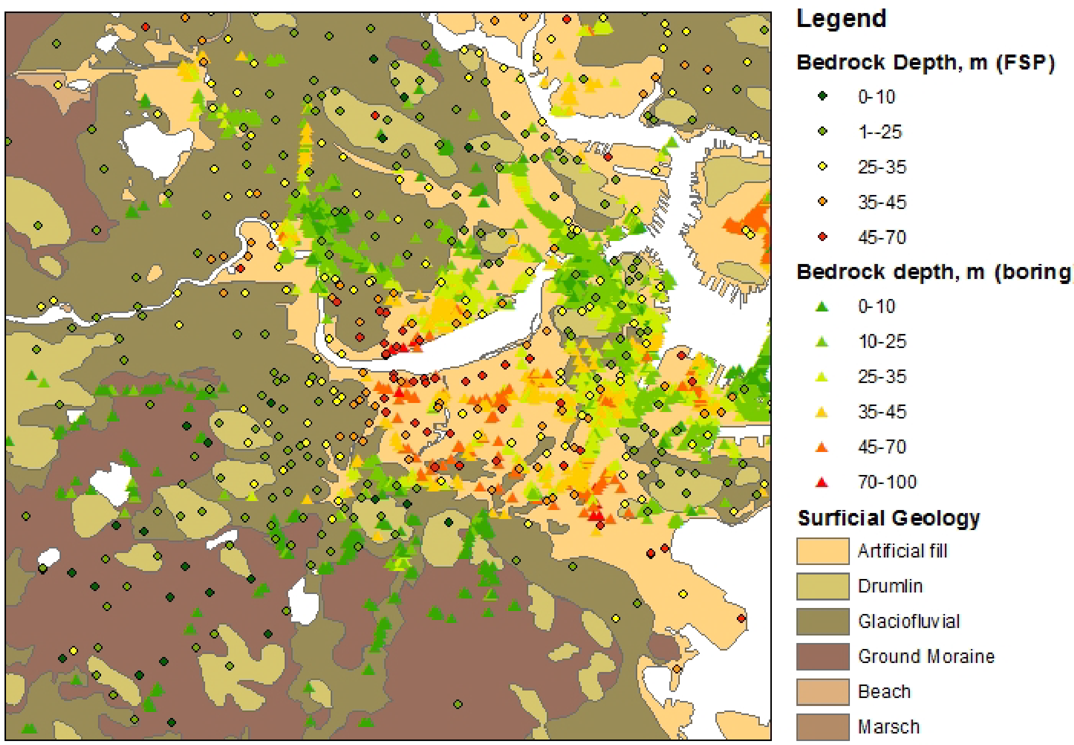

Figure 14 – Observed and predicted depth to bedrock across Boston.

V_{S30} Comparison

V_{S30} values, defined as the travel-time weighted average shear-wave velocity to 30-m depth (Borcherdt, 1992), were available in the region from 27 SASW measurements (Thompson et al., 2013) and 3 sCPT measurements (Santagata and Kang, 2007). Of these 30 velocity profiles, 21 V_{S30} values reported and 5 Vs profiles didn't extend to 30 m but were extrapolated to Vs30 by Litton (2015). The 26 V_{S30} sites were visited for H/V FSP measurements as part of this study. One of the sites, 921ACM, is a glaciofluvial site and had been reported as having a very high V_{S30} (1853 m/s) after extension to 30 m by Litton (2015). This site was removed from the V_{S30}/FSP correlation analysis because of the incompatibility between the V_{S30} value and the surface geology at this site and the lack of nearby borehole data to confirm the local stratigraphy. Figure 14 shows the correlation between V_{S30} and FSP for this study as compared with similar relationships for other regions. The data are fit with a power function with a coefficient of determination (R^2) of 0.88. The best-fit line for Boston is similar to the two recently published relationships from Ottawa (personal communication) and Montreal, Canada (Chouinard and Rosset, 2012) which are also shown in Figure 15. Both Ottawa and Montreal have sediments over hard bedrock with a high impedance contrast. The Ottawa relation is highly consistent with the Boston relation. The best-fit curve for Montreal (Chouinard and Rosset, 2012) is also in good agreement with the Boston curve, although it shows slightly lower V_{S30} values compared to Boston at small FSP values and greater V_{S30} values at larger FSP values.

$$V_{S30} = a * FSP^b \qquad (3)$$

Coefficients (with 95% confidence bounds):

$a = 150.2\ (100.2,\ 200.2)$

$b = -0.7716\ (-0.8487, -0.5745)$

$0.05 \le \text{FSP} \le 0.95$

Ghofrani and Atkinson (2014) report a V_{S30} and FSP relationships based on the NGA West 2 database for the western U.S. and on a comprehensive database from Japan. Their results are compared with those from the Boston data in Figure 14. The Ghofrani and Atkinson (2014) Japan curve is similar to the curves found both in this study and in the two Canadian cases. Ghofrani and Atkinson (2014) report that the global relation given in Ghofrani and Atkinson (2014) is based on the NGA West 2 database which is dominated by events from California. The Ghofrani and Atkinson (2014) global relation results in significantly higher Vs30 values than the other relations at FSP values greater than 0.2 s. This difference may be explained by the comparably low impedance contrast between overlying sediments and bedrock in California compared to the shallow soil layers over relatively harder bedrock observed in eastern North America.

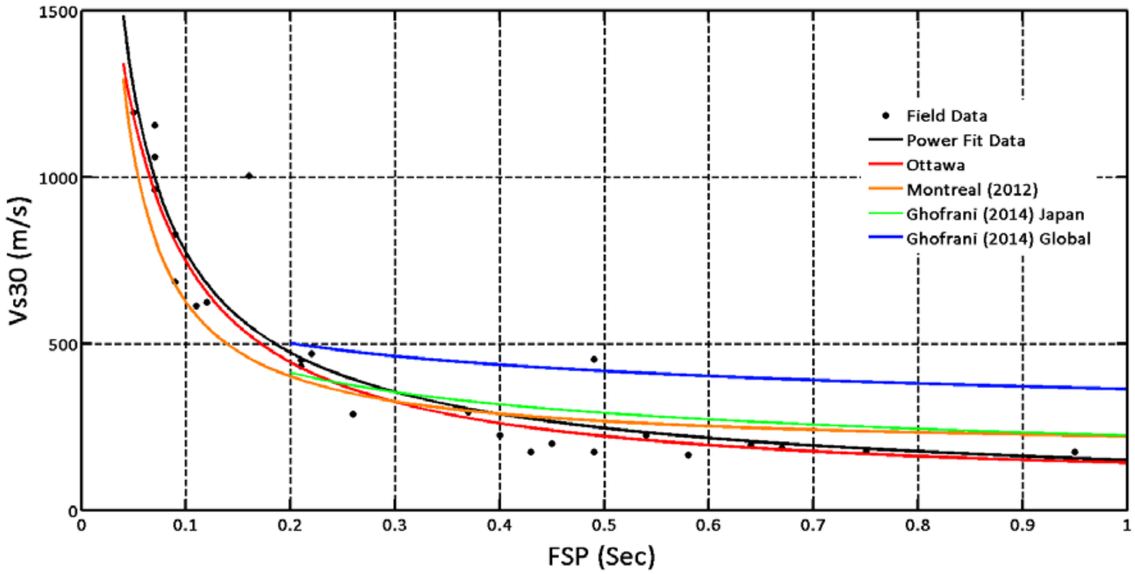

Figure 15. Plot of FSP and V_{S30} from the Boston area dataset. The relationship obtained for Boston is in good agreement with the curves previously published for other high impedance-contrast regions.

Site Response Validation

Using the generic Vs profile in Figure 2b, we investigated site response for typical bedrock depths across the region as summarized in Baise et al. (2016). The summary of the soil amplification is shown in Figure 16.

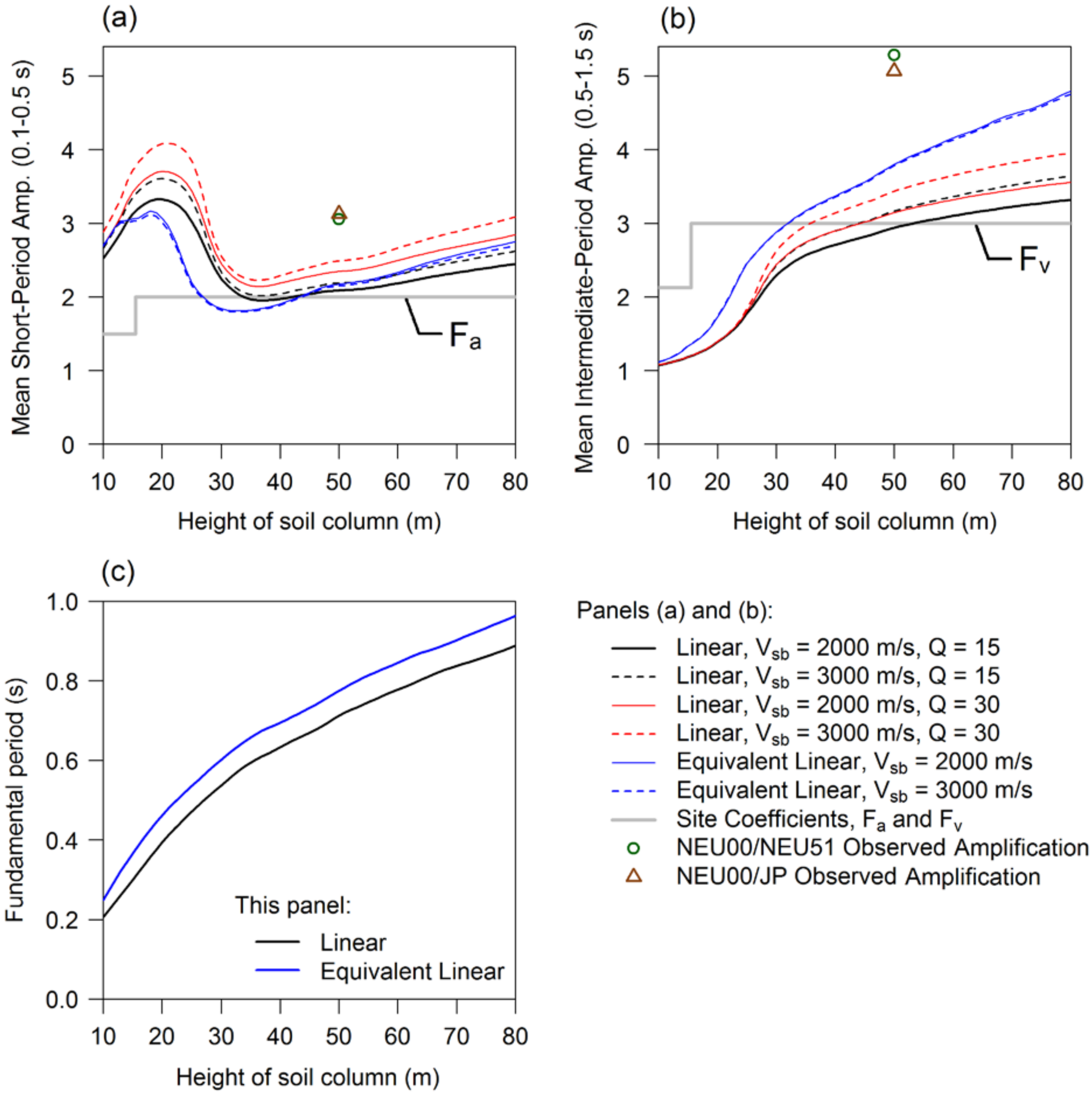

Figure 16. Mean amplification and fundamental period versus depth to bedrock (for various linear and equivalent-linear models, including the F_a and F_v lines): (a) mean short-period amplification, (b) mean intermediate-period amplification, and (c) fundamental period. The lines for the site coefficients have been selected based on the design ground-motion levels for Boston (selected for site class A), as well as the average shear-wave velocities of the profiles. The profiles with H ≤ 15 m are site class C, and the profiles with H > 15 m are site class D (hence the discontinuity at H = 15 m). Also shown are the observed mean amplifications for the Northeastern University surface/downhole pair (NEU00/NEU51) and surface/outcrop pair (NEU00/JP) (taken from Baise et al., 2016).

Conclusions

Ambient noise data collected at 570 sites were used to derive relationships between FSP, surficial geology, depth to bedrock and V_{S30}. Mapping efforts showed that the FSP values are in good agreement with the underlying surficial geology layers and that surficial geology units can be used to estimate expected FSP. H/V ratios derived from earthquake recordings from the NEU vertical array, the NEU Snell Engineering Center and the MIT Green Building are consistent with the H/V ratios derived from ambient vibration recordings. Overall, the robust relationships between FSPs from ambient noise data and both depth to bedrock and V_{S30}, as well as the consistency between FSPs estimated from earthquake events and from ambient vibration data, show the power and the reliability of the H/V ratio method in assessing the site response in earthquake shaking when there is a strong impedance contrast between surficial sediments and hard bedrock in places like Boston.

A linear relationship between FSP and depth to bedrock can be used to estimate depth to bedrock from ambient noise H/V ratios. Another relationship was developed to estimate Vs30 with FSP. The FSP/V_{S30} curve for the Boston dataset is consistent with curves found in Ottawa and Montreal in Canada and may be representative of FSP/V_{S30} correlations in other high impedance-contrast environments as well.

Using the boring data for the region to characterize a generic soil profile, we evaluate site effects as dependent on soil column depth (see Baise et al., 2016, for a full description).

Bibliography

1. Baise, L.G., Kaklamanos, J., Berry, B., and Thompson, E.M. (2016). Soil amplification with a strong impedance contrast: Boston, Massachusetts. *Engineering Geology*, **202** (1-13).
2. Yilar, E., Baise, L.G., and Ebel, J. (in review). H/V MEASUREMENTS TO DETERMINE DEPTH OF BEDROCK AND V_{S30} IN BOSTON, MASSACHUSETTS, A HIGH IMPEDANCE CONTRAST ENVIRONMENT *Engineering Geology*, submitted.

References

Baise, L.G., Kaklamanos, J. Berry, B.M., and Thompson, E.M. (2016). Soil amplification with a strong impedance contrast: Boston, Massachusetts. *Engineering Geology,* **202**, 1-13.

Bodin, P., Smith, K., Horton, S., and Hwang, H. (2001). Microtremor observations of deep sediment resonance in metropolitan Memphis, *Tennessee, Eng. Geol.* 62, 159–168.

Borcherdt RD. (1992). Simplified site classes and empirical amplification factors for site dependent code provisions. In: NCEER, SEAOC, BSSC workshop on site response during earthquakes and seismic code provisions Proceedings, University Southern California, Los Angeles, CA, Nov18-20; 1992.

Brankman, C. M. and Baise, L. G. (2008). Liquefaction Susceptibility Mapping in Boston, Massachusettts, *Engineering and Environmental Geoscience,* XIV (1), pp. 1-16.

Butterworth, S. (1930). "On the theory of filter amplifiers," Experimental Wireless and the Wireless Engineer, vol. 7, pp. 536–541

Çelebi, M., Toksöz, N. and Büyüköztürk, O., (2014). Rocking behavior of an instrumented unique building on the MIT campus identified from ambient shaking data, *Earthquake Spectra*, v30, no.2, pp.705-720, May 2014

Chouinard, L. and Rosset, P. (2012). On the Use of Single Station Ambient Noise Techniques for Microzonation Purposes: the Case of Montreal; in *Shear Wave Velocity Measurement Guidelines for Canadian Seismic Site Characterization in Soil and Rock*, (ed.) J.A. Hunter and H.L. Crow; *Geological Survey of Canada, Open File 7078,* p. 85-93.

Coffman, J.L., von Hake, C.A., and Stover, C.W. (1982). *Earthquake history of the United States: Publication 41-1*, Rev. Ed. (with supplement through 1980), National Oceanic and Atmospheric Administration and U.S. Geological Survey, Boulder, Colo., 258p.

Ebel, J.E. (1996). The seventeenth century seismicity of northeastern North America, *Seismological Research Letters* 67, 51-68.

Ebel, J.E. (2006). The Cape Ann, Massachusetts Earthquake of 1755: A 250th Anniversary Perspective, *Seismological Research Letters* 77, 74-86.

Ghofrani, H. and Atkinson G. M. (2014). Site condition evaluation using horizontal-to-vertical response spectral ratios of earthquakes in the NGA-West 2 and Japanese databases, *Soil Dynamics and Earthquake Engineering,* 67, 30-43.

Hashash, Y. M., Kottke, A. R., Stewart, J. P., Campbell, K. W., Kim, B., Moss, C., Silva, W. J. (2014). Reference Rock Site Condition for Central and Eastern North America. *Bulletin of the Seismological Society of America*, 104(2), 684-701.

Hales, J. G. (1819). Map of Boston and Its Vicinity.

Hayles, K.E., Ebel, J.E. and Urzua, A. (2001). Microtremor Measurements to Obtain Resonant Frequencies and Ground Shaking Amplification for Soil Sites in Boston, *Civil Engineering Practice* 16 17-36.

Johnson, E.G. (1989). “Geotechnical characteristics of the Boston area.” *Civil Engineering Practice* 4(1), 53-64

Kaye, C. A. (1979). Engineering Geologic Framework of the Boston Basin. *Engineering Geology in New England*, edited by AW Hatheway, 1-18.

Kaye, C. A. (1982). Bedrock and Quaternary geology of the Boston area, Massachusetts. Geological Society of America *Reviews in Engineering Geology*, 5, 25-40.

Ladd, C.C. & Edgers, L. (1972). "Consolidated-undrained direct simple shear tests on Boston Blue Clay," Research report R71-13, Department of Civil Engineering, MIT, Cambridge, MA.

Litton, D. (2015). Vs30 Correlations for the Boston Area. M.S. Thesis. Tufts University.

Mitchell, J. K. (1956). The importance of structure to the engineering behavior of clay: Sc. D. Thesis, M.I.T.

Nakamura Y. (1989). Y.A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Q. Rep. RTRI 30, 25–33.

Santagata, M & Kang, Y. (2007). Effects of geologic time on the initial stiffness of clays. *Engineering Geology*, 98–111

Site EffectS Assessment using AMbient Excitations (SESAME) (2004). Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations; measurements, processing, and interpretation, European commission - Research General directorate, Project No. EVG1-CT-2000-00026 SESAME, 62 pp.

Sykes, L.R., J.G. Armbruster, W.Y. Kim and L. Seeber (2008). Observations and Tectonic Setting of History and Instrumentally Earthquakes in the Greater New York City-Philadelphia Area, *Bull. Seism. Soc. Am.* 98, 1696-1719.

Swan, C., and Greene, C. (1998). “Freeze-thaw effects on Boston Blue Clay.” Soil improvement for big digs, A. Maher and D. S. Yang, eds., ASCE, Reston, Va. 161–176.

Trudeau, P. T., Whitman, R. V. and Christrian, J. T. (1974). Shear-wave velocity and modulus of a marine clay, *J. Boston Soc. Civil Engr.*,61, No. 1, 12–25.

Thompson, E.M., Kayen, R.E., Carkin, B., Baise, L.G. (2014). Surface Wave Site Characterization at 27 Locations Near Boston, Including 2 Strong Motion Stations, *U. S. Geological Survey OFR 2014-1232*.

Thompson, E.M., Barry, B., Zhu, J., Baise, L.G., Ebel, J., and Rodgers, A.J. (2013). Developing and Validating a Community Velocity Model for Boston. *Seism. Res. Lett.* Vol. 84, No. 2, p. 300.

Tuttle, M.P., Witkowski, A., Daniszewska, G., Ebel, J. and Myskowski, E. (2003). Evidence for a Large Earthquake near Newburyport, Massachusetts about 2,000 Years Ago, *Seism. Res. Lett.* 74, 253.

Wong, I., Tera, F., Rukstales, K., Becker, L., Bausch, D., Rozelle, J., Morey, P., Ebel, J., and Fratto, E. (2012). HAZUS Analyses of Eleven Scenario Earthquakes in New England, report to FEMA by URS Corp.

Yegian, M. K. (2004) Seismic Recording Station At Northeastern University Boston, Massachusetts.