Using H/V Measurements to determine depth to bedrock and V_{s30} in Boston, Massachusetts

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Seismic microzonation is an important step in seismic risk and loss studies for densely populated urban regions. 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 (shear-wave velocity, $V_s=200$ m/s) overlays hard glacial till or bedrock ($V_s =2000-3000$ m/s). In this study, 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, is applied to determine the FSP. The FSP data are mapped across the region and show a consistent pattern with the local geologic and geomorphologic conditions. The FSP data are then paired with depth to bedrock and V_{s30} drawn from 2403 boring logs and 25 V_s profiles (V_{s30} is defined as the time-weighted average of the V_s in the upper 30 m of the soil profile). The depth to bedrock and FSP are correlated, as are FSP and V_{s30} measurements. FSP/depth to bedrock and FSP/ V_{s30} correlations are reported with 95% confidence bounds for use in regional planning. The resulting FSP/ V_{s30} correlation is comparable with similar studies from high impedance contrast regions in Canada and Japan and show lower V_{s30} for sites with

FSP > 0.2 s (where the FSP predicts depth to bedrock > 18 m) than previously reported for the NGA-West2 database. The accuracy of single station ambient noise results is also confirmed with single-station and vertical-array earthquake spectral ratios. An FSP (~0.74 s) was calculated from ambient noise data at the Northeastern University (NEU) Vertical Array site in the Back Bay of Boston. At this site the sediment thickness is 51 m and is consistent with the FSP (~0.73 s) calculated for the site using earthquake records from the 2011 Mw 5.8 Mineral, Virginia earthquake. 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. When the FSP estimates are paired with additional data such as depth to bedrock, V_{s30} estimates, and recorded ground-motion data, the spatial distribution of regional site effects can be characterized.

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. In tectonically active regions of the United States, many 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 in the Central and Eastern United States (CEUS), similar investigations for urban regions in CEUS have been comparatively limited (i.e., Memphis and St. Louis). Recent moderate earthquakes in CEUS such as 2011 Mw 5.8 Mineral, Virginia earthquake have brought attention to the potential earthquake risk to cities in low to moderate seismicity regions, especially for the high-population density eastern seaboard. In CEUS, resources are limited, and therefore, we need to characterize

regional soil amplification with limited data. In many parts of CEUS, bedrock shear-wave velocities are high (>2 km/s; e.g. Hashash et al., 2014) leading to strong impedance contrasts at the soil/bedrock interface. Soil amplification due to strong impedance contrasts have been observed in regions such as Boston, Massachusetts (Baise et al., 2015) and Ottawa, Canada (Banab et al. 2012) and can significantly affect damage patterns, as observed in Mexico City during the 1985 earthquake (Seed et al., 1988; Kramer, 1996).

Microtremor studies using Nakamura's technique (Nakamura, 1989, Lermo and Chavez-Garcia, 1994), which involves taking the ratio of the Fourier amplitude noise spectra of the horizontal component to that of the vertical component (H/V), have proven useful in strong impedance-contrast environments to estimate the fundamental site period (FSP) (Chouinard and Rosset, 2012; SESAME, 2004; Hayles et al., 2001). To better understand the wave propagation physics of the H/V ratios in Nakamura's technique, Bonnefoy-Claudet et al. (2006) performed simulations to test the relationship between source location, wave type and H/V ratios. Bonnefoy-Claudet and others (2006) concluded that since the majority of observed H/V spectral ratios resulted in single peaks and that H/V peaks are primarily controlled by local sources and the result of the ellipticity of the fundamental Rayleigh waves. Many authors have used the H/V defined FSP with stratigraphy to determine sediment thickness by developing correlations between the two variables (Guo et al., 2014; Del Monaco et al., 2013; Walling et al., 2009; Parolai et al., 2002; Bodin et al., 2001; Ibs-von Seht and Wohlenberg, 1999). Some studies go a further step and have used the results from microtremor studies to estimate the seismic soil amplification through simple 1D soil amplification functions (Di Giulio et al., 2008).

While H/V studies are common in Europe (Del Monaco et al., 2013; Di Giulio et al., 2008; SESAME, 2004; Parolai et al., 2002; Ibs-von Seht and Wohlenberg, 1999) and the Mississippi

embayment (Guo et al., 2014; Rosenblad and Goetz, 2010; Bodin et al., 2001), H/V studies have been limited in the CEUS. The work presented herein builds on the Hayles et al. (2001) study that demonstrated that H/V microtremor could be used to identify the FSP in Boston. 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.

Boston, Massachusetts is an urban region exposed to low 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. In Boston, we have assembled 2403 soil borings with depth to bedrock information, 25 V_S profiles with V_{S30} estimates (V_{S30} is defined as the time-weighted average of the V_S in the upper 30 m of the soil profile), earthquake ground-motion records at two surface stations and one downhole array, surficial geology, and a history of artificial fill. Given 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. In this paper, we develop quantitative relationships between FSP, surficial geology conditions, depth to bedrock and V_{S30} for our dataset. These relationships can be used to predict depth to bedrock and V_{S30} at uncharacterized sites. In addition, ground-motion records from two sites are used to verify that H/V estimates of FSP are similar for ambient noise and earthquake ground motion. The goal of this study is to provide estimates of depth to bedrock and FSP across the region for use in future soil amplification mapping studies.

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.

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 shear-wave velocities are typically between 200 and 400 m/s whereas near-surface shear-wave bedrock velocity is on the order of 2000 m/s (Baise et al., 2016). Using 2403 soil 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. Typical bedrock depths range from 12 to 75 m near the Charles River and 24 to 38 m along the Mystic Rivers. The soil boring database spatial coverage decreases inland and away from downtown Boston.

A vertical array with three-component seismometers has been operated for a number of years at a site close to the Northeastern University Snell Engineering Center (NEU, 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

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4 121 clays, glacial till and bedrock. The bedrock depth is 51 m at the site with a Boston Blue Clay
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6 122 thickness of 43 m. The 2011 Mineral event was also recorded by a seismometer at 2 km distance
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9 123 from NEU in Jamaica Plain at Jamaica Pond (rock site, $V_{s30}=961$ m/s, Thompson et al., 2014).
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11 124 The effects of local site conditions have been studied and summarized in Baise et al. (2016), and
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14 125 the spectral ratio of the surface and bedrock recordings at NEU is shown in Figure 3. The
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16 126 spectral ratio shows that the amplification between the soil and bedrock can be characterized as a
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19 127 single resonance and results in approximately 10 times spectral amplification at the fundamental
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21 128 site period of 0.7 s. To check these results, we conducted one-dimensional (1D) linear site
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24 129 response analysis with the NEU stratigraphy and shear-wave velocity by using the 2011 Mineral
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26 130 earthquake recorded at the Jamaica Pond site as the bedrock ground motion. More details of the
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29 131 response analysis are given in Baise et al. (2016). Figure 3 provides evidence that both the
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31 132 observed and predicted transfer functions for a typical soil site in Boston show a strong
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34 133 resonance at a fundamental site period. This result demonstrates the significance of the local site
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36 134 conditions in Boston, the accuracy of the 1D linear site response assumption, and the importance
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38 135 of the fundamental site period in characterizing site response in Boston.
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44 138 **Data Collection**

45 139 Ambient noise data collection and analysis relies on the collection of continuous time series data
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48 140 of ambient vibrations. The instrumentation consisted of a three-component Guralp CMG-40T
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50 141 broadband seismometer and a Reftek RT-130 datalogger. The data were sampled at 100 Hz.
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53 142 From 17 August to 29 December 2014 ambient noise data measurements were collected from
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55 143 570 locations in the greater Boston area by visiting each site for 15 minutes of data recording.
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Our spatial sampling plan roughly followed a grid with a spacing of about 500 m for approximately 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 with two sets of instruments to maximize data collection over a short time period. A huddle test was performed with the instruments used in the experiment both prior to and after the data collection phase to insure consistency between the two instrument sets. The huddle test results showed that the instrument responses were 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. The Hayles et al. (2001) and Kummer (1998) study demonstrated that the FSP estimates were consistent during daytime and nighttime hours but that the peaks were better defined during daytime hours when the noise levels are higher. For safety reasons all of the data were collected during daytime. The locations where measurements were made were selected to avoid subways and other potentially hollow subsurface locations such as sewage and sanitary lines.

H/V Analysis

Data processing was performed uniformly across the dataset of 570 ambient noise measurements. The time series were detrended and then the first 120 -180 s were removed from the time history to eliminate noise due to the operator turning on and walking away from the instrument. Because of low frequency microseismic energy that is outside our frequency range of interest, we applied a 4th order Butterworth band-pass filter (Butterworth, 1930). 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

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4 167 Hz (matching the Nyquist frequency). The low-cut frequency of 0.5 Hz means that we cannot
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6 168 identify any FSP greater than about 2 s. Given the range of sediment thickness in the region and
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9 169 the results of Hayles et al. (2001), the highest FSP that we expect is between 1-1.5 s, and so the
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11 170 low-cut corner was selected to easily pass these periods. After filtering, each record (typically
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13 171 600-900 s) was divided into 10 non-overlapping windows of data of 40 s length. An FFT was
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15 172 computed for each 40-s data window and then the 10 amplitude spectra were stacked for each
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18 173 component. We used a 20-point moving average to smooth the stacked spectra.
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22 174 Using these stacked and smoothed amplitude spectra, the amplitude spectral ratio H/V (ratio of
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24 175 the horizontal to vertical amplitude spectra) was computed for each of the horizontal components
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27 176 of motion. In most cases, a clear narrow peak with a similar period range was observed in the
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29 177 H/V ratio from each of the horizontal components as shown in Figure 4. The FSPs from each
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31 178 component were averaged to provide the FSP for the site. The standard deviation of the
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33 179 differences between the horizontal component FSP estimates for all sites was found to be 0.09 s.
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36 180 From tests of the band-pass filter, small variations in the corner frequencies of the filter did not
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39 181 affect the FSP value, although the changes did impact the amplitudes of the spectral ratio values.
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44 183 **Ambient Noise versus Earthquake Data**

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48 185 Maine earthquake at the MIT Green Building provided an opportunity to further verify the
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51 186 ambient noise results with earthquake recordings. The spectral ratios of the horizontal
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53 187 components to the vertical component were determined and compared to the results from
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56 188 microtremor H/V ratios for each site.
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Results for NEU are shown in Figure 5 where 5a shows that the H/V ratios at the surface (FSP= 0.81 s and 0.88 s for the two horizontal components) as compared to the traditional surface/downhole spectral ratios (FSP=0.73 s and 0.68 s for the two horizontal components). The second peak in the spectral ratios near 0.25 s and 0.27 s in Figure 5a for the H/V spectral ratios of the surface and depth records may correspond to S-wave harmonics 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 a seismometer 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 5b. The observed peak in Figure 5b is wide and may consist of the combination of two modes of vibration. As a result of this wide peak, the FSPs of 0.64 s and 0.82 s are more variable than generally observed. This may be a result of a building resonance as it is not observed in Figure 5a and 5c which are both measured at the ground surface. Finally, we compare the H/V ratios derived from earthquake recordings with the H/V ratios derived from ambient vibration recordings at a nearby location as shown in Figure 5c. The ambient noise H/V ratios result in FSPs of 0.74 s and 0.73 s for each component (Figure 5c). In summary, FSPs for the ground sites are consistently estimated between 0.74 s to 0.88 s using both earthquake and ambient noise H/V ratios as well as surface/downhole spectral ratios. This range provides an appropriate resolution for site characterization as discussed in the depth to bedrock section.

To further verify 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 Maine Earthquake was recorded by the seismic monitoring system

comprising 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 6a and show that both of the H/V spectral ratios resulted in a FSP of 0.60 s with a clear peak. We also collected ambient vibration data at a site 150 m away from the MIT Green Building. The results of these analyses are given in Figure 6b where the FSPs occur at 0.63 s and 0.70 s, indicating that the earthquake and ambient noise FSP estimates are again consistent. In this example, the amplifications are noticeably different with higher values for the earthquake recordings. In this paper, we have chosen to focus on FSP estimation because of the inconsistent ability of H/V to identify accurate amplification ratios. In the following sections, we discuss the implications of the variability in FSP assessment across the sites.

Mapping of FSP

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 7 to show spatial trends in the local site conditions. In Figure 7, a similar pattern can be observed between the surficial geology and the H/V determined FSPs where higher FSPs are consistently found where we expect deeper sediments and lower FSPs are consistently found where we expect thin sediments.

In Figure 8a and 8b, we compare the FSP results in Back Bay, Cambridgeport, and South Boston to historical maps that show areas historically covered by water which were filled in the 19th

century (Figure 8a). The observed FSPs in these areas are 0.35 s – 1.05 s (Figure 8b) and the bedrock depth in these regions ranges from 20-70 m. The same pattern is 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 8c). We also observe high FSPs between the Mystic Lakes and Fresh Pond which are mapped as glaciofluvial surficial deposits (Figure 8d). 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 Pond (Figure 8e). 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. One of the most interesting locations is from the Chelsea area as shown in Figure 8f. While the measurements around the Island End River show low FSPs, high fundamental periods are observed about 1 km to the north followed by low FSPs toward the drumlins. A historical map (e.g., Hales, 1819) reveals that at one time Island End River extended in the north and northeast direction into Chelsea as shown in Figure 8f. Therefore, these locations most likely have artificial fill atop thick sediments associated with the flood plain of the former river channel.

The FSP dataset is plotted with box plots as a function of surficial geology in Figure 9. Artificial fill and glaciofluvial deposit sites correspond to high (median=0.5 s) and moderate (median=0.3 s) FSPs, respectively, and drumlin and ground moraine sites result in low (median=0.14 s) to very low (median=0.05 s) 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 FSP. If surficial geology was used to map typical FSP values by using the interquartile range,

the FSP ranges shown in Table 1 would be appropriate. The interquartile range captures the middle 50% of the distribution.

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 is plotted using boxplots as a function of surficial geologic unit in Figure 10. Figure 10 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 relation between rock and glacial till. In general, glacial till overlies bedrock generally with a thickness of a few meters. The high variability of the depth to bedrock at drumlin sites may be attributed to a thick glacial till layer or misidentification of bedrock due to the hard nature of both materials.

In Figure 11, 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 one-to-one so 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 and plotted in Figure 11. A linear relationship is observed in Figure 11 and given in Equation (1). In Equation (1) H is the depth to bedrock and p_1 and p_2 are linear regression constants. The coefficient of determination (R^2) in Figure 11 is 0.67, suggesting that the data have a linear trend but with a large amount of scatter.

The scatter is not surprising given that the borings and FSP measurements are not colocated and can be separated up to 250 m. The FSP-depth to bedrock relationship should be used with the confidence bounds. For example, an FSP of 0.7 s would lead to a 95% confidence interval for the depth to bedrock of between 38-52 m. In addition, FSP estimates can vary on the order of 0.1 s at a site; therefore, an average FSP of 0.7 s would lead to a 95% confidence interval for the depth to bedrock between 35-56 m. Although this is a large depth range, it still provides a first order estimate for planning purposes. For simplicity in this linear regression fit, we did not force the line through zero; however, we recommend that the non-zero intercept (p2) is not meaningful, but rather it is a further indication of the large scatter in the data.

$$H = p1 * FSP + p2 \quad (1)$$

Coefficients (with 95% confidence bounds):

$$p1 = 54.68 \text{ (47.95, 61.41)}$$

$$p2 = 7.47 \text{ (4.55, 10.38)}$$

$$0.03 \leq FSP \leq 0.85$$

The 95% confidence bounds are shown in Figure 11 and can be used to evaluate the confidence in the best fit line.

V_{S30} Comparison

V_{S30} values (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 were reported by the authors and 5 Vs profiles didn't extend to 30 m but were extrapolated to V_{S30} 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 surficial geology at this site. Figure 12 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 given in equation 2 with a coefficient of determination (R^2) of 0.88. Coefficients are given with 95% confidence bounds shown in parentheses below and as gray solid lines in Figure 12.

$$V_{S30}=a*FSP^b \quad (2)$$

$$a=150.2 \text{ (100.2, 200.2)}$$

$$b=-0.7716 \text{ (-0.8487, -0.5745)}$$

$$0.05 \leq FSP \leq 0.95$$

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) also shown in Figure 12. 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.

Ghofrani and Atkinson (2014) report 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 also compared with those from the Boston data in Figure 12. 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 their reported global curve is based on the NGA West 2 database which is dominated by events from California. The Ghofrani and Atkinson (2014) global curve results in significantly higher V_{S30} values than the other relations at FSP values

greater than 0.2 s. This difference may be related to differences in geology and resulting V_s structure of the sediments and underlying bedrock in California compared to the shallow soil layers over relatively harder bedrock observed in eastern North America. These results provide preliminary evidence that a common FSP V_{s30} relationship may exist for regions with similar near surface geology as observed in Ottawa, Montreal, Boston, and possibly Japan.

In Figure 12, the curve is relatively flat for FSP greater than about 0.4 s, whereas it steepens as FSP decreases below 0.4 s. This is consistent with Figure 11, where 30 m depth corresponds to an FSP of 0.42 s. Thus, at FSP values greater than 0.42 s, the thickness of the soil layer is greater than 30 m and the FSP is measuring an average velocity for a full stack of sediments. Below a FSP of 0.42 s, some of the V_{s30} value includes the velocity of the bedrock, and so that value should be higher than simply the velocity of the soils. For very small FSP the bedrock must be very close to the surface and so the V_{s30} must be very high.

Usage for Soil Amplification Mapping Studies

The results presented above can be used in regional soil amplification mapping for the Boston area. The FSP estimates can be mapped as shown in Figure 7 or interpolated across the region to be used by structural engineers to estimate soil/building resonance. The FSP or the depth to bedrock can also be used directly with the results of Baise et al. (2015) to estimate the soil amplification coefficients F_a and F_v across the region. For example, for $T=0.8$ s, equation 1 predicts $H=51$ m and equation 2 predicts $V_{s30}=178$ m/s. Using the results from Baise et al., (2015) for equivalent linear site response for Boston, a $T=0.8$ s matches an $H=54$ m and can be used to estimate appropriate F_a and F_v using Figure 11 in Baise et al (2015). Each of these uses can take into account the variability in FSP as well as in equations 1 and 2.

Conclusions

Ambient noise data collected at 570 sites are used to derive relationships between FSP, surficial geology, depth to bedrock and V_{s30} . H/V ratios derived from earthquake recordings from the NEU vertical array, the NEU Snell Engineering Center and the MIT Green Building are found to be consistent with the H/V ratios derived from ambient vibration recordings. The distribution of FSP values by surficial geology layers show differentiation for mapping purposes where the sediments underlying the artificial fill have higher FSP (median = 0.5 s) than those underlying glaciofluvial sediments (median = 0.3 s). Materials mapped as drumlin or ground moraine consistently have low FSP (median = 0.14 s and 0.05 s respectively). Furthermore, a linear relationship is derived between FSP and depth to bedrock and can be used to predict depth to bedrock from FSP. The uncertainty in this relationship is given as confidence bounds in Figure 11. Because FSP correlates with depth to bedrock, FSP can be used as a cost-effective mapping tool to identify shallow and deep sediments and can be linked to soil amplification through the studies summarized in Baise et al. (2015) which provide F_a and F_v soil amplification functions in terms of FSP and depth of bedrock. Maps of FSP for Boston identify deep sediment channels that are mapped as part of the surficial geology.

Using the data from this project, a correlation was derived between FSP and V_{s30} . The FSP/ V_{s30} curve for the Boston dataset is consistent with curves found in Ottawa and Montreal in Canada, as well as Japan, and may be representative of FSP/V V_{s30} correlations in other high impedance contrast environments. Above an FSP of 0.42 s (equivalent to $H=30$ m), the V_{s30} values tend to be lower than those observed in California (through the NGA-West 2 dataset as shown by Ghofrani et al. 2014). When $FSP < 0.42$ s and $H < 30$ m, the V_{s30} rises sharply as the high shear-wave velocity of the bedrock is included. H/V studies are highly recommended for similar

regions with a strong impedance contrast in the near surface, where resonance can be easily detected by the fundamental site period.

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Figures

Figure 1. Typical V_s profiles in Boston by surficial geologic unit. The dotted lines show individual V_s profiles, the dark black line shows an average profile for each geologic unit, and the gray shows the 95% confidence intervals for each geologic unit.(from Baise et al., 2016)

Figure 2. 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.

Figure 3. Site amplification at Northeastern University (NEU). From Baise et al. (2016). Observed and predicted transfer functions for the Mineral, Virginia earthquake at the NEU vertical seismometer array. The predictions are plotted for a generic V_s profile in artificial fill with a bedrock depth of 50 m. A linear site response model is used with $V_{sb} = 3000$ m/s and $Q = 30$.

Figure 4. H/V analysis plots for a site having high FSP a) Fourier spectra of the three components (b) Ratios of the Fourier spectra of each horizontal-to-vertical component.

a

b

c

Figure 5. (a) Spectral ratios from the NEU Vertical Array of the 2011 Mineral earthquake showing the H/V spectral ratios 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 to nearby to the NEU Vertical Array site.

a

b

Figure 6. (a) H/V spectral ratios of the recordings of the 2012 Waterboro, Maine earthquake from the basement of the MIT Green Building (b) H/V spectral ratios of ambient noise data from a site nearby to the MIT Green Building

Figure 7. 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 8. Overlay of FSP from H/V measurements onto surficial geology maps and the 1819 Boston and its vicinity map. (a, b) the downtown area. Historically filled areas shown in orange show higher FSP values than land areas. (c) FSPs along the Mystic River are higher than those away from the river (d) Observed high FSPs between Mystic Lake and Fresh Pond can be explained by the deeper sediment thickness in this area. (e) FSPs along the Charles River are the highest in the region (f) Historic east and northeast extension of the Island End River is associated with local relatively higher FSPs.

Figure 9. Distribution of FSP as a function of surficial geologic unit in terms of a boxplot. The red crosses show outliers (beyond the whisker length = interquartile range).

Figure 10. 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. The red crosses show outliers (beyond the whisker length = interquartile range).

Figure 11. Depth to bedrock versus FSP. The best-fit line is shown in grey with 95% confidence bounds (dashed).

Figure 12. Plot of FSP and V_{s30} from the Boston area dataset. The best fit line is shown in solid black with 95% confidence bound in solid gray. The relationship obtained for Boston is in good agreement with the curves previously published for other high impedance contrast regions (Montreal and Ottawa).