V_{s30} Correlations for the Boston Region

A thesis submitted by

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Abstract

Engineers need V_{s30} values for use in earthquake design. Currently in Boston, most projects do not include shear wave velocity (Vs) data due to the high cost of their collection. V_{s30} is time-averaged shear wave velocity in the upper 30 meters of the soil profile. This study analyzed different methods for regional estimates of V_{s30} using surficial geology, topographic slope, and H/V estimates. The H/V spectral ratio is a ratio of the spectra of horizontal and vertical ground motions. The H/V spectral ratio can be used to estimate the fundamental site period which can then be correlated with V_{s30}. In Boston, we had 27 V_{s30} values and 560 H/V estimates of V_{s30}. Elevation and surficial geology data were also available across the study region. Boston surficial geology is governed by Pleistocene glaciation, coastal marine sediments, and artificial fill. As a result, the majority of V_{s30} values are in 3 surficial geologic units: artificial fill, ground moraine/bedrock, and glaciofluvial deposits. In Boston, the topographic slope method for estimating V_{s30} has a strong bias towards NEHRP Class C. Comparatively, the H/V estimates of V_{s30} range from NEHRP Class B to Class D (>760 m/s to 180 m/s) and are consistent with the measured V_{s30}. A map of the region was created using the average H/V estimates of V_{s30} by geologic unit. One finding of this work is that an improved zonation of the V_{s30} map could be made with an improved surficial geology map (finer classifications). For example, the glaciofluvial deposit could be separated into shallow and deep sediments.

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Introduction

Engineers in Boston have a need for understanding local site conditions in order to facilitate the seismic building design process. To characterize site conditions for seismic design, the building code uses time-averaged shear wave velocity of the top 30 meters of the subsurface (V_{s30}) as a measurement of soil stiffness. V_{s30} values are used to determine NEHRP site class. The NEHRP site class is used to predict the extent of the amplification that can be expected at a site through F_a and F_v amplification factors. Soils with low V_{s30} values are expected to have large site amplification. Direct V_s measurements are not typical for design projects due to the high cost of collecting shear wave velocity profiles. Direct V_s measurements are, therefore, typically reserved for large projects, like the Big Dig (a large tunneling project in Boston), and the Stata Center at MIT (Santagata et al., 2007), and for research projects (Thompson et al., 2014). Currently, in Boston, there are 30 V_s profiles available in the open literature.

Proxies of V_{s30} are often used in place of direct measurements for the assessment of site effects and to determine earthquake design loads. Several methods exist to estimate site effects locally when only limited data are available. Possible correlations include geology-based average V_{s30}, topographic slope/V_{s30} correlations, and H/V fundamental site period/V_{s30} correlations (Becker et al, 2013; Magistrale et al, 2012; Wald and Allen, 2007; Yilar et al., 2015). Geology-based site effect estimates are derived by assigning NEHRP site class to each geologic unit (Becker et al, 2013). This method is based on work from California where available V_{s30} values were averaged within geologic units (Wills and Clahan, 2006). The topographic slope-based V_{s30} correlation uses the topographic slope at locations where V_{s30} has been directly measured to create a correlation between slope and V_{s30} (Wald and Allen, 2007). Since the topographic slope-based V_{s30} correlation depends on the net effects of geologic erosion and depositional processes, i.e. Wald and Allen (2007), the reliability of that correlation may not be very good for the glaciated topography of Boston. The geologic erosion and depositional processes carry loose soils, i.e. alluvial plains and outwash, out into low slope areas where they settle out while the stiff soils and rock are left as high slope landforms. The H/V spectral ratio is a ratio of the spectra of horizontal and vertical ground motions. The H/V spectral ratio can be used to estimate the fundamental site period, and the fundamental site period has, in turn, been correlated with V_{s30} (Bard et al., 2005; Yilar et al., 2015). The current study aims to analyze the available correlations and determine the most suitable correlation for producing a proxy V_{s30} map of the Boston region.

This study is part of a larger Tufts University project on studying earthquake site effects in Boston. The project is comprised of these efforts:

- Thompson et al. (2014) collected shear wave velocity profiles at 27 sites in Boston using the spectral analysis of surface waves method.

- Numerous borehole data cataloged by the Boston Society of Civil Engineers Sections (BSCES) (1969 – 1984) were digitized by others at Tufts University.
- Boston has been analyzed for liquefaction potential by Brankman and Baise (2008), who also developed a surficial geology map of the region.
- Site amplification effects were analyzed by Berry (2014) at 11 sites along the Charles River.
- Most recently, microtremor H/V data have been collected at 560 locations and related to V_{s30} with a regional correlation by Yilar et al (2015).

Background

Surficial Geology

Boston bedrock is a combination of slate, argillite and conglomerate within the Boston Basin which is bordered mostly by granite. The bedrock is overlain by glacial materials, Boston Blue Clay, and artificial fill, depending on the area. At the time of its founding, Boston was made up of small islands with the city center near Beacon Hill. Beacon Hill was a tidal island with parts of the land being flooded during high tides. Much of the city of Boston is built on artificial fill that was laid during the first expansion of Boston. Many of the historical buildings in Boston are still on the original fill. Newer construction has replaced the original artificial fill on the sites with engineered fill, which tends to be denser with a wider grain size distribution. Typically, the fill can range from 0 – 20 feet thick, underlain by 10 – 80 feet of Boston Blue Clay, and then bedrock (Johnson, 1989). Throughout that typical stratigraphy, irregularities such as layers of sand and gravel and glacial till of varying thickness can be found.

The cities and towns surrounding Boston are mostly underlain by shallow glacial sediments over bedrock. Some of the surrounding areas, such as Cambridge and Alewife, were also historically filled (Johnson, 1989). The glacial sediments include glacial till, glaciofluvial deposits, glacial moraines, and glacial drumlins. These glacial formations are typically poorly sorted combinations of sand, gravel, silt, and clay (Brankman and Baise, 2008). Glacial till, moraines, and drumlins are typically associated with stiff soils while glaciofluvial deposits are outwash and are expected to have lower strength and stiffness values. Isolated areas along rivers and some coastal areas have marsh deposits. Beach deposits can also be found in isolated coastal areas.

The surficial geology map, Figure 1, was developed by a geologist as a generalized map in order to determine liquefaction susceptibility of Boston (Brankman and Baise, 2008). The geology was generalized to form only 6 geologic units. Glaciofluvial deposits contain a large variety of specific geologies like outwash, eskers, kettles, kame fields, and terraces. The ‘ground moraine’ unit is a combination of bedrock and ground moraine deposits. The two were combined because bedrock daylights within the thin ground moraine deposits, and the two would both behave similarly with respect to liquefaction. Other units are artificial fill, marsh deposits, and beach deposits, as described above. There are recognizable subsurface units that are well known in the Boston area such as the Boston Blue Clay but because these units do not extend into the surface they were not mapped (Brankman and Baise, 2008). The Boston Blue Clay is found primarily beneath the artificial fill geologic unit although it extends beneath the glaciofluvial deposits as well.

Slope-based V_{s30} Method

The topographic slope correlation was first used in a Wald and Allen study in California (Wald and Allen, 2007). The method uses the mean slope to assign a V_{s30} value for tectonically active or stable continental classified areas. The method has recently been adapted to other regions (Becker et al., 2011; Iwahashi et al., 2010; Lemoine et al., 2012; Magistrale et al., 2012) as well as extended to include additional parameters (Iwahashi et al., 2010; Thompson et al., 2014; Yong et al., 2012). It is also mostly used on a regional basis, such as across an entire state or across a country (Becker et al., 2011; Iwahashi et al., 2010; Magistrale et al., 2012; Thompson et al., 2014). Iwahashi et al. used a 50-m DEM to map the site class of Japan at 1646 locations of known V_{s30} through slope gradient, surface texture, and logarithm of elevation. The team found a blend of the three variables that provided a strong normal distribution of the residuals for the 1646 sites. Thompson et al. (2014)

used topographic slope in combination with known V_{s30} and surficial geology to create a robust mapping technique for California. The benefit of this technique is that it uses supplied combination of slope and geology to more accurately map the estimated V_{s30} at the site. They believe that the technique can be applied to regions outside of California.

The Becker et al. (2011) paper analyzed the potential of a topographic slope proxy as a replacement for the current HAZUS-MH mapping in New England. Becker et al. chose sample sites where the geology was well understood. The authors made geologic site class maps using a method developed by Cadwell (2003) for application in New York State. With an accepted geologic site class map of each sample area, the 30 arcsec Wald and Allen correlation for stable continental regions was applied. The group determined that the equation provided an approximately 50% match rate which was not suitable for their purpose of hazard loss estimation. Becker et al. (2011) determined that a sweeping designation of Class D was preferred for the HAZUS-MH project in order to prevent underestimation of damage. Magistrale et al. (2012) applied the Wald and Allen approach to three regions for the U.S.: Western US, Rocky Mountains, and Central and Eastern US (CEUS). The CEUS region covers all of the states from the Rocky Mountains east. They used the proprietary V_{s30} observation database of Pacific Engineering and Analysis. The research team created new models for the slope - V_{s30} correlation for each region. Magistrale et al. assessed their mapping accuracy through the analysis of bias and the natural logarithm of standard deviation.

Microtremor Methods

Nakamura (1989) created a method that uses vertical (V) and horizontal (H) components of microtremor data to estimate predominant frequency and amplification factor. Nakamura (1989) determined that the spectral ratio of the horizontal and vertical components was similar to the transfer function of surface layers. This technique is now commonly referred to as the Nakamura technique or H/V spectral ratios. Lin et al. (2014) used H/V spectral ratios as a reliable estimate of the site-transfer function for S-waves in the Taipei basin. Yilar et al. (2015) performed H/V microtremor analysis for the Boston basin using ambient noise data collected at 560 locations. Using the H/V spectral ratio analysis, the predominant period was calculated at all 560 sites and was used to develop a correlation with V_{s30}.

Bonilla et al. (1997) used S-wave, Coda, and H/V methods to estimate site effects. The study used the three methods on aftershocks from the Northridge earthquake to estimate site effects. Bonilla et al (1997) determined that H/V is capable of showing the predominant period of the site but provided a different amplification factor than the other two methods. The study also determined that a detailed geology classification from Tinsley and Fumal, 1985 was superior to geology classifications based on the 1:750,000 geology map of California for estimating average site response. The 1:750,000 geology classifications were Quaternary, Q, Tertiary, T, and Mesozoic. The detailed classification map groups some of the ages by average Vs30.

An extension of the H/V microtremor Nakamura technique was tested in Greece and Taiwan by Theodulidis and Bard (1995). The study concluded that the Greek stations showed a stable correlation based on the low standard deviation of the spectral ratio. The H/V spectral ratios from the Greek sites were also comparable to results from other microtremor tests in both the frequency range of amplification and in absolute level.

Theodulidis et al. (1996) analyzed 110 accelerograms to check the use of H/V spectral ratio as an indicator of site effects. Like the other studies, the H/V ratio was found to be a stable estimate of fundamental site period using standard deviation. The amplification values from the H/V ratio were consistent with local geologic structure and were insensitive to the source location or source mechanism. The insensitivity provides evidence to support the use of H/V ratio in both microtremor estimates and strong motion estimates.

A guideline for using and interpreting H/V microtremor data was made by SESAME (SESAME, 2004). SESAME stands for Site Effects assessment using Ambient Excitations. It is a guideline that was produced by a European group of researchers and aims to create practical procedures for understanding and using microtremor data. The guide has parts for field work, data interpretation, data processing, and result interpretation. The team also included examples and diagrams in the appendices.

Data

Twenty-seven shear-wave velocity profiles, 560 H/V spectral ratios, and a surficial geology map are available for the Boston area and are summarized in Table 1 (V_s) and plotted on Figure 1.

The H/V data were collected as microtremor data by Yilar et al. (2015). Microtremors are small ground vibrations caused by non-seismic events. H/V data are analyzed from the ratio of the averaged horizontal and the vertical components. The H/V spectral ratios can also be used to constrain the depth to bedrock which has been correlated with V_{s30} (Yilar et al., 2015).

Twenty-seven of the V_s profiles were collected through the spectral analysis of surface waves (SASW) (Thompson et al., 2014) while 3 were collected with the seismic cone penetration test (Santagata and Kang, 2006). The twenty-seven V_s profiles collected by Thompson et al. (2014) have been rated for quality and span across the study area. The SASW method uses a parallel array of mass shakers with frequencies between 1 and 200 Hz. The shakers produce Rayleigh surface waves which are then processed. The dispersion of the Rayleigh waves provides information about the shallow shear wave velocity. The Rayleigh wave to shear wave approximation is expected to have less than 10 percent error (Thompson et al. 2012). The calculation uses a frequency domain analysis and is made on multiple signals. The signals are transformed into their equivalent linear spectrum using a Fourier transform. The separation of the reference seismometer, usually the sensor closest to the source, and the output seismometer radially is then used to compute the velocity.

Twenty-six of the V_s profiles from the Thompson et al (2014) report were used in this study. Four of the measurements, 907BVA, 914LQN, 915LQF, and 916LQT, exist outside of the surface geology map and were excluded. Several of the V_s profiles did not have calculated V_{s30} values in the Thompson et al (2014) report. The V_{s30} for 902MVP was calculated by performing the standard calculation of weighted averages based on the V_s profile, since the profile extended through to the full depth of 30m. Four of the shear wave velocity profiles resulted in profiles less than 30 meters deep and needed to be extended to 30 meters depth. 920RPK, 921ACM, 922SQM, and 923EPD were extended by calculating the average shear wave velocity to the maximum measured depth and then using the equation from Boore et al. (2011) to extend them to 30 meters. Station 911JVA was recalculated due to a visual analysis of the profile appearing to have a higher V_{s30} value than was reported.

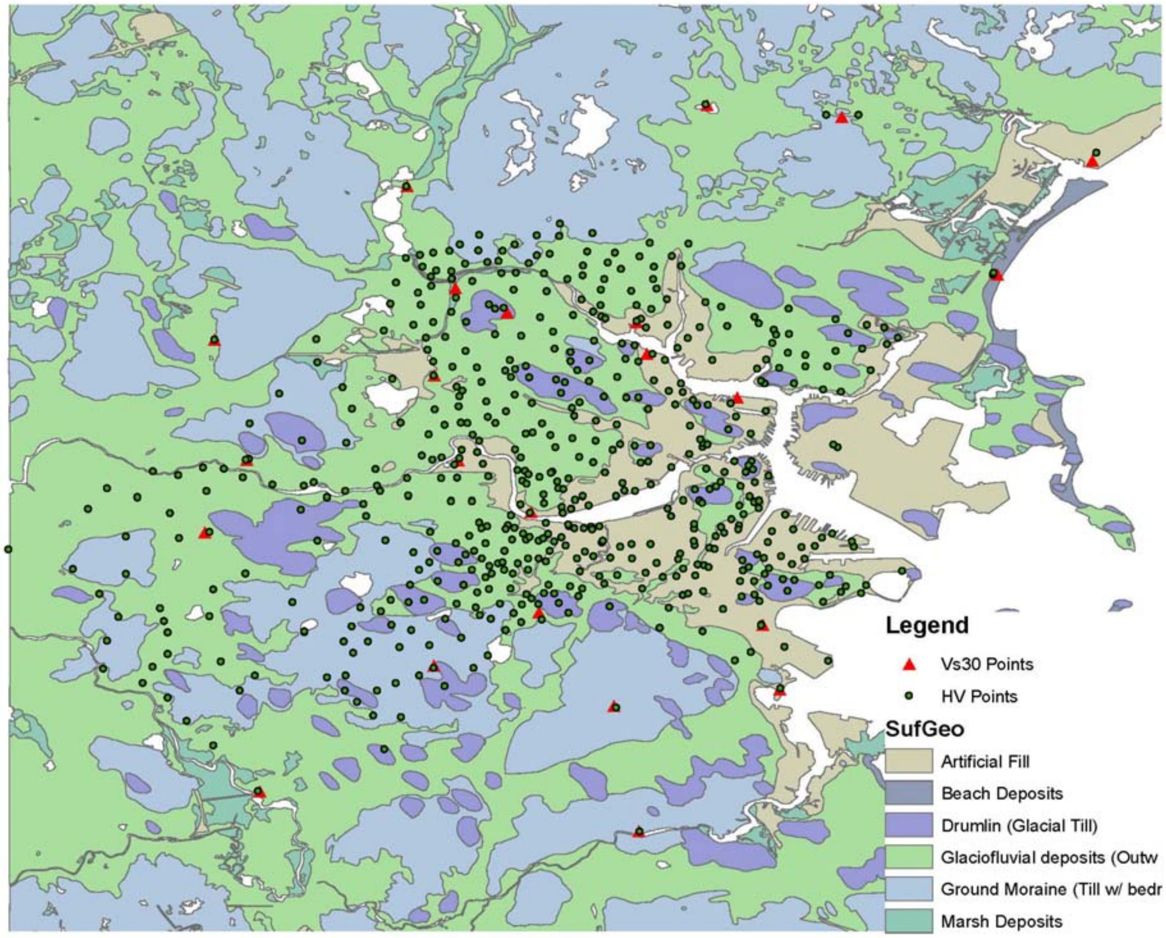

Figure 1: Surface Geology (colors, keyed to legend), V_{s30} measurement locations (red triangles), and H/V measurements (green circles). (Brankman and Baise 2008; Thompson et al., 2012; and Santagata et al., 2007.)

Table 1: V_{s30} measurement location information. Geology is read from the map in Figure 1.

Station	Latitude	Longitude	$V_{S30\_}$ m/s	$Z_{1.0\_}$ m	Grade	Geology
902MVP	42.41353	-71.13226	1004	10	C	Marsh
903TUF	42.40702	-71.11858	828	10	A	Drumlin
905MVP	42.44048	-71.1449	470	15	C	Glaciofluvial
906RMC	42.3998	-71.19569	1155	3	C	Bedrock
907BVA	42.50348	-71.27363	747	7	A	Bedrock
908DP	42.39029	-71.13772	199		B	Glaciofluvial
909BUB	42.35435	-71.11231	295	50	A	Fill
910LAP	42.3136	-71.1379	1193	5	C	Bedrock
911JVA	42.32773	-71.11013	1680	3	C	Glaciofluvial
912SFR	42.36781	-71.13146	195		A	Fill
913FPZ	42.30303	-71.09047	1061	5	C	Bedrock
914LQN	42.5522	-71.52042	1532	2	C	Quarry
915LQF	42.55532	-71.52036	1734	2	B	Quarry
916LQT	42.55105	-71.51586	492	30	C	Quarry
918MAC	42.40442	-71.08444	187		A	Fill
919MIL	42.2803	-71.18375	289		A	Glaciofluvial
920RPK	42.2698	-71.08384	684	22	A	Bedrock
921ACM	42.39607	-71.08168	452		C	Fill
922SQM	42.45873	-71.03031	613	26	C	Bedrock
923EPD	42.46197	-71.06586	1859	5	C	Glaciofluvial
924JMP	42.32452	-71.05112	176		A	Fill
925MAL	42.30738	-71.04671	165		A	Fill over fluvial
926WAT	42.36804	-71.18718	624	5	B	Glaciofluvial
927NCP	42.34898	-71.1982	450	10	B	Glaciofluvial
928LFP	42.44725	-70.96424	174		A	Fill
929WON	42.41708	-70.98927	431	15	A	Beach
931WTC	42.38457	-71.0579	178		B	Fill
103EB	42.369427	-71.026785	175			Fill
102SB	42.369387	-71.047378	225			Fill
100MIT	42.3617	-71.0907	225			Fill

Drumlins, marsh deposits, and beach deposits only have one V_{s30} measurement each; the last two cover relatively small areas in Figure 1. The primary geologic units of interest for this study are therefore artificial fill, glaciofluvial, and ground moraine (bedrock). Glaciofluvial deposits have seven V_{s30} measurements, artificial fill has eleven V_{s30} measurements and ground moraine has six V_{s30} measurements. The locations in ground moraine were labeled as bedrock in the original USGS report. A summary of the V_{s30} data by geology is made in Table 2.

Stations 911JVA and 923EPD, as seen in Figures 2 and 3, have unusually high V_{s30} values for the glaciofluvial deposits likely due to the presence of shallow bedrock. In 911JVA, harder material is encountered at about 4 meters below ground surface; and in 923EPD, harder material is encountered at about 6 meters below ground surface.

The only marsh deposit station has a measured value of 1004 m/s. This is a very high value for the marsh deposits geologic unit, presumably due to shallow bedrock (Figure 4). Further, due to the location of the measurement, the surface geology is believed to be glaciofluvial deposits rather than marsh deposits.

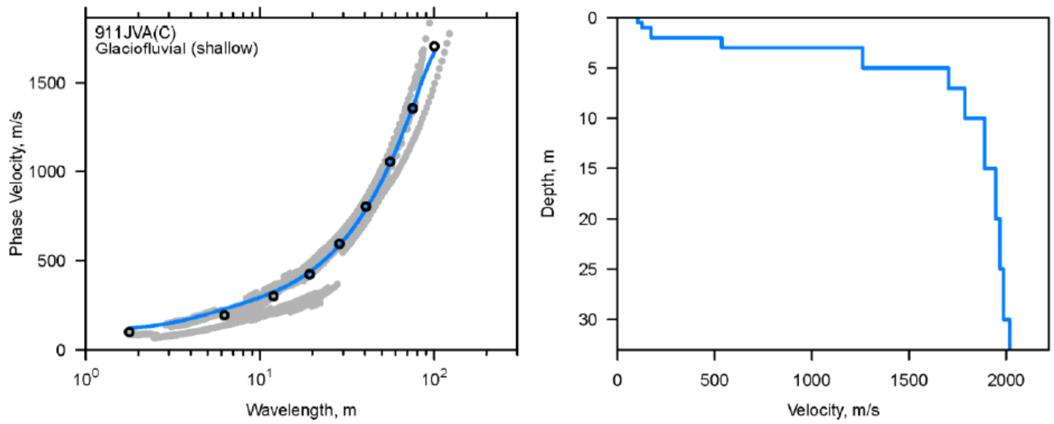

Figure 2: V_s profile of glaciofluvial deposits station 911JVA showing rock by 5m depth. Thompson et al., 2014.

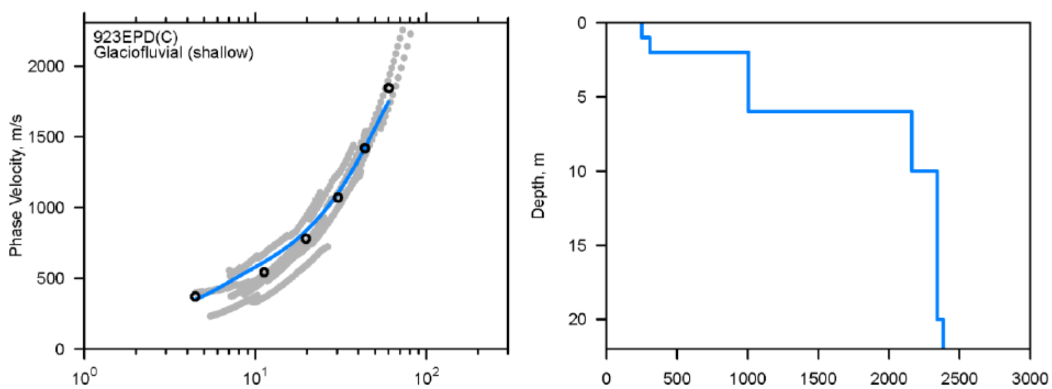

Figure 3: V_s profile of glaciofluvial deposits station 923EPD showing rock at 5m depth. Thompson et al., 2014.

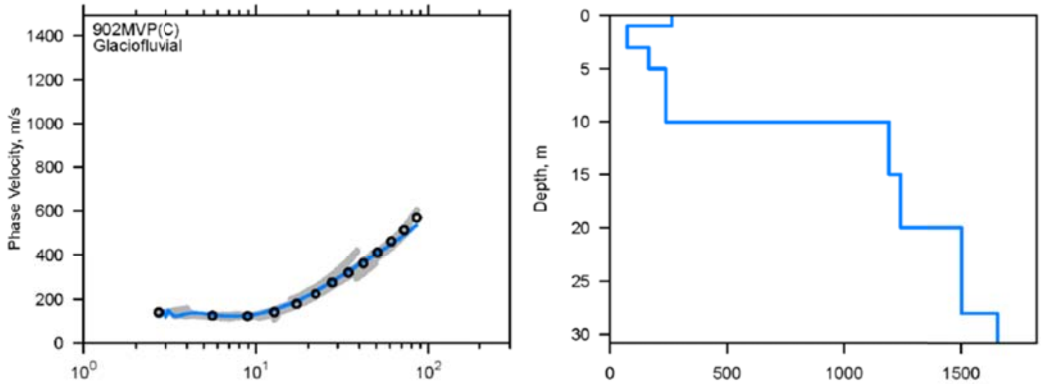

Figure 4: V_s profile of marsh deposits station 902MVP showing rock at 10m depth. Thompson et al., 2014.

The H/V-based V_{s30} data were taken from Yilar et al. (2015). All of the H/V data were used to determine statistics on the data set. A summary of the H/V data is in Table 2.

Table 2: Summary of H/V and V_{s30} data

	Average H/V based V_{s30}	Standard Deviation of H/V based Vs30	Count of H/V measurements	Average measured V_{s30} value	Standard Deviation of measured V_{s30} values	Count of measured V_{s30} Values
Drumlin	722	430	58	822	-	1
Glaciofluvial Deposits	438	311	278	895	680	7
Ground Moraine	1123	446	52	908	256	6
Artificial Fill	238	102	167	199	85	11
Beach Deposits	425	0	2	431	-	1
Marsh Deposits	400	140	3	1004	-	1
Total			560			27

Results

The goal of this project was to determine the best method for mapping the site response category (in terms of V_{s30}) using some combination of topographic slope, surficial geology, V_{s30} estimates from V_s profiles, and V_{s30} estimates from H/V fundamental site period. To determine the best mapping method, correlations between these parameters were analyzed. The topographic slope was tested in 3 arcsec, 9 arcsec, and 30 arcsec resolutions using the published Wald and Allen (2007) (30 arcsec) and Allen and Wald (2009) (9 arcsec) correlations for stable continental regions. The topographic slope data were plotted against V_{s30} to examine the scatter and reasonableness of the correlation. The topographic slope was also plotted against the H/V estimated V_{s30} values to determine if a larger sample would show a better correlation. The topographic slope V_{s30} estimates and H/V V_{s30} estimates were grouped by surficial geology. Glaciofluvial deposits, artificial fill, and ground moraine were chosen as the geologic units to study due to the number of available data and coverage area. The measured V_{s30} measurements were used as benchmarks to determine how well the correlations were performing. The values of the measured V_{s30}, H/V estimated V_{s30}, and topographic slope estimated V_{s30} averaged over geologic units were also compared to characterize the geologic units, and to help eliminate the bias that could derive from a small comparison sample. From these estimates, the best performing correlation was chosen and applied, on each geologic unit, to create a V_{s30} proxy map.

Slope-based V_{s30} Correlation

The first V_{s30} approximation technique used was the Wald and Allen topographic slope correlation. The topographic slope method (Wald and Allen, 2007) follows the assumption that high strength soils and rock will be able to sustain larger slope gradients while the lower strength materials are washed into flat plains. Originally, Wald and Allen tested topographic slope at 30 arcsec or 1 km grid spacing. Separately, Allen and Wald (2009) looked into the applicability of higher resolution topographic slope maps in the correlation. In the analysis of higher resolution dataset, Allen and Wald (2009) analyzed 3 arcsec, and 9 arcsec or approximately, 90, and 270 meters grid spacing. Allen and Wald (2009) determined that the higher resolution can better identify small regions of rapidly changing slope (as in tectonically active areas), but that some smoothing (i.e., 30 arcsec) gives more reliable slopes, particularly in low-gradient areas (such as tectonically inactive areas).

Digital elevation data were downloaded from ESRI as GTOPO 30 arcsec data and 3 arcsec SRTM data. The 3 arcsec SRTM data were resampled into a 9 arcsec dataset through bilinear interpolation. The slope was then calculated through the slope function in ArcGIS as percent rise using the appropriate z-factor. The z-factor is used to calculate the slope when the units of the elevation and lateral distance are in different units. The Wald and Allen 30 arcsec and 9 arcsec correlation, seen in Table 3, was applied in the Boston area to the region covered by the surficial geology map. The 9 arcsec correlation was applied to both the 9 arcsec slope and 3 arcsec slope, as shown in Figures 5a and 6a, because a correlation has not been published for the 3 arcsec slope.

The 30 arcsec resolution elevation and slope maps shown in Figure 4a provide too much smoothing and remove details of the known Boston topography such as the drumlins and moraines. The 3 arcsec resolution seems to identify the geology clearly as seen in Figure 6a but an accepted, published correlation is lacking to calculate the V_{s30}. The Wald and Allen plots of V_{s30} vs. topographic slope were made to analyze the parameter bins as seen in Figures 4b, 5b, and 6b. Figures 4b, 5b, and 6b show significant scatter. The scatter of these plots indicates that a correlation cannot be easily made for the Boston region.

Table 3: Wald and Allen topographic slope to V_{s30} correlation

NEHRP Site Class	V_{s30} Range (m/s)	9s Gradient Range (m/m)	30s Gradient Range (m/m)
E	<180	<1E-4	<2.0E-5
D-	180-240	1E-4-4.5E-3	2.0E-5-2.0E-3
D	240-300	4.5E-3-8.5E-3	2.0E-3-4.0E-3
D+	300-360	8.5E-3-0.013	4.0E-3-7.2E-3
C-	360-490	0.013-0.022	7.2E-3-0.013
C	490-620	0.022-0.03	0.013-0.018
C+	620-760	0.03-0.04	0.018-0.025
B	>760	>0.04	>0.025

The Wald and Allen correlation as presented in Table 3 is limited on the upper and lower bounds at 760 and 180 m/s. The upper bound limits the hard rock identification that exists in stable continental regions, which have shown that the V_{s30} values can rise as high as 1800 m/s (Table 1). The hard-set bins of the correlation also remove intermediate V_{s30} values that would better identify the region. As can be seen in Table 3, the bins can have a significant V_{s30} range, especially in the site classes for harder material. In this study, the average value of each bin was applied to the slope range.

H/V Correlation

The H/V estimated V_{s30} were also plotted against topographic slope as seen in figures 4c, 5c, and 6c. The H/V estimates have 560 V_{s30} values and a strong correlation to the V_{s30} values at each site (Yilar et al., 2015). The scatter in the larger sample shows that the correlation between topographic slope and V_{s30} is not strong in the glaciated landscape of Boston. The 9 arcsec slope map has a similar visual result as the 3 arcsec map, identifying the key geologic units: drumlin and ground moraine. The 9 arcsec map lacks some of the fine detail that the 3 arcsec map has but the high topographic resolution can produce unstable slope estimates (Allen and Wald, 2009). The 9 arcsec plot appears to have the best correlation out of the three topographic resolutions. For these reasons, the 9 arcsec map, which still shows the details of the glacial geology and has an industry accepted correlation, was chosen.

An H/V- V_{s30} correlation for Boston was created by Yilar et al (2015). The V_{s30} correlation was used to convert from fundamental site period to V_{s30} at each of the 560 H/V locations. The H/V estimates of V_{s30} were averaged by surficial geologic unit as summarized in Table 2. The H/V estimates of V_{s30} and Allen and Wald topographic slope estimates of V_{s30} were compared with the measured V_{s30} points to determine the accuracy of the method as shown in Figures 5a – 7c and Tables 4-9. On an individual station basis, the H/V data is consistently closer to the measured V_{s30} value than the Allen and Wald approximation. For the 3 geologic units of interest (Glaciofluvial Deposits, Artificial Fill, and Ground Moraine), the H/V average is closer to the V_{s30} average and each V_{s30} point than the Wald and Allen correlation.

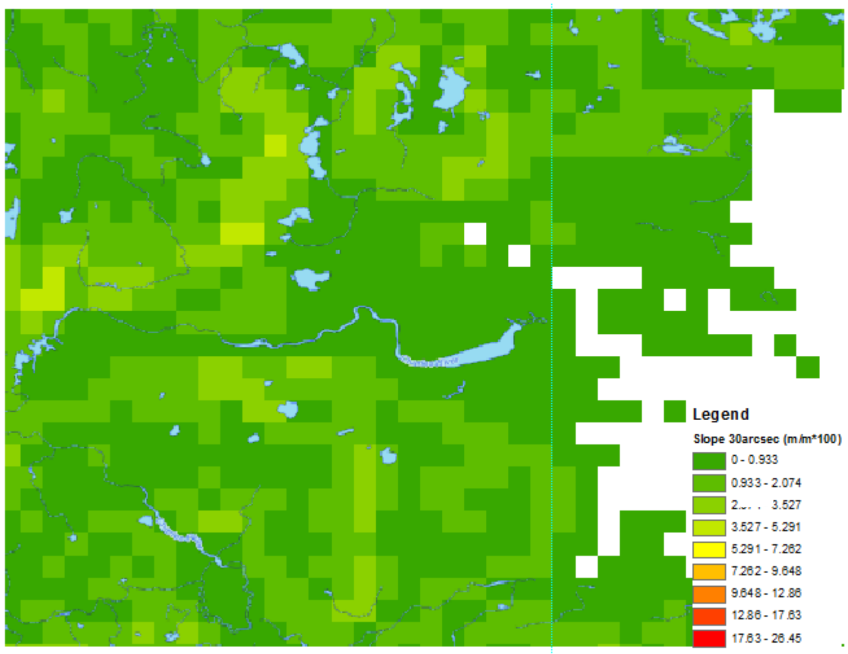

Figure 5a: Wald and Allen 30 arcsec slope Map

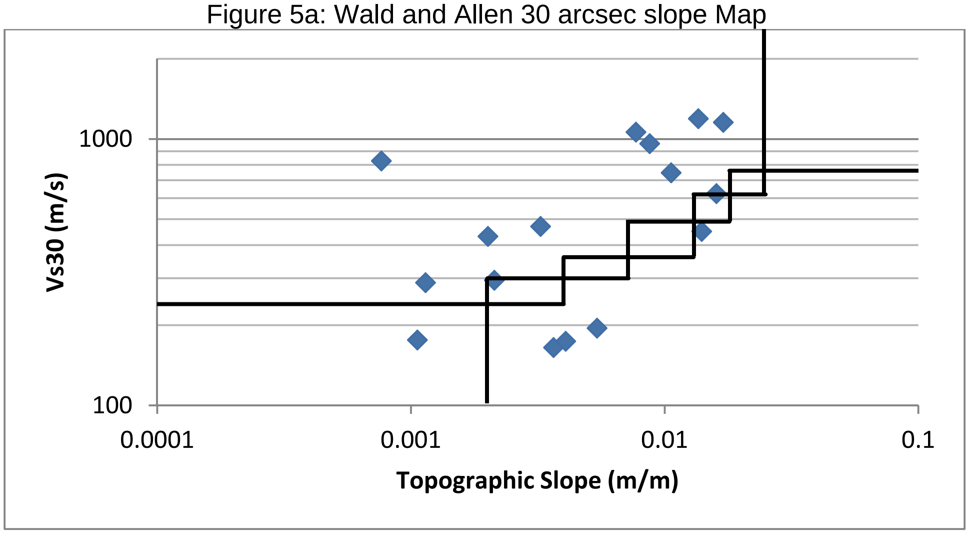

Figure 5b: V_{s30} versus 30 arcsec resolution topographic slope

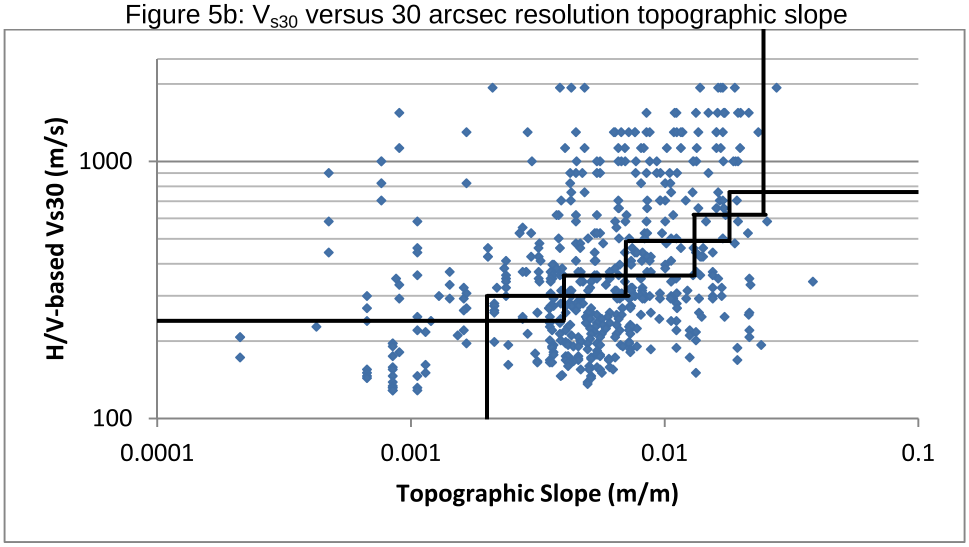

Figure 5c: H/V estimated V_{s30} versus 30 arcsec topographic slope

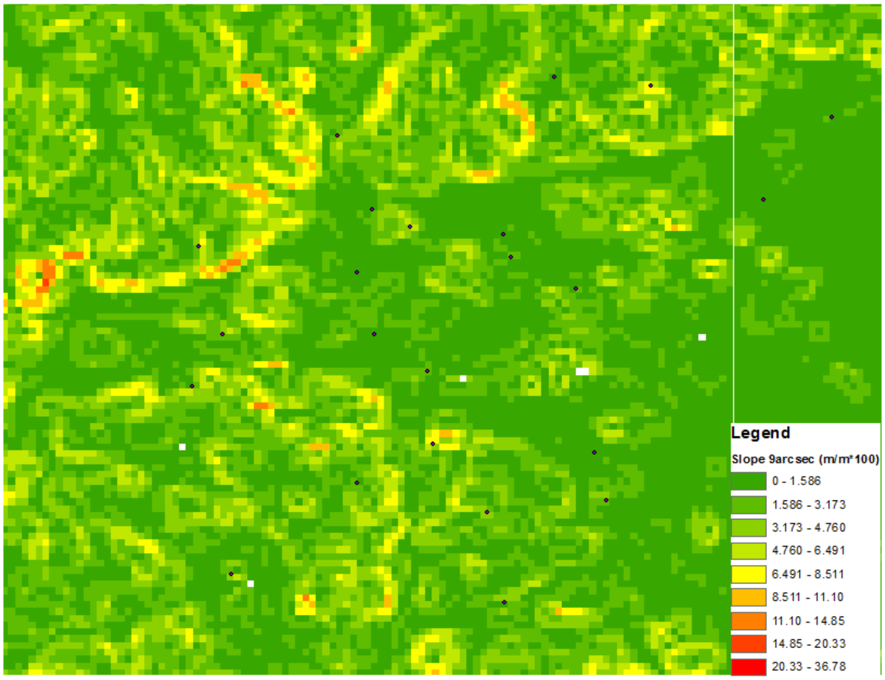

Figure 6a: Wald and Allen 9arcsec slope Map

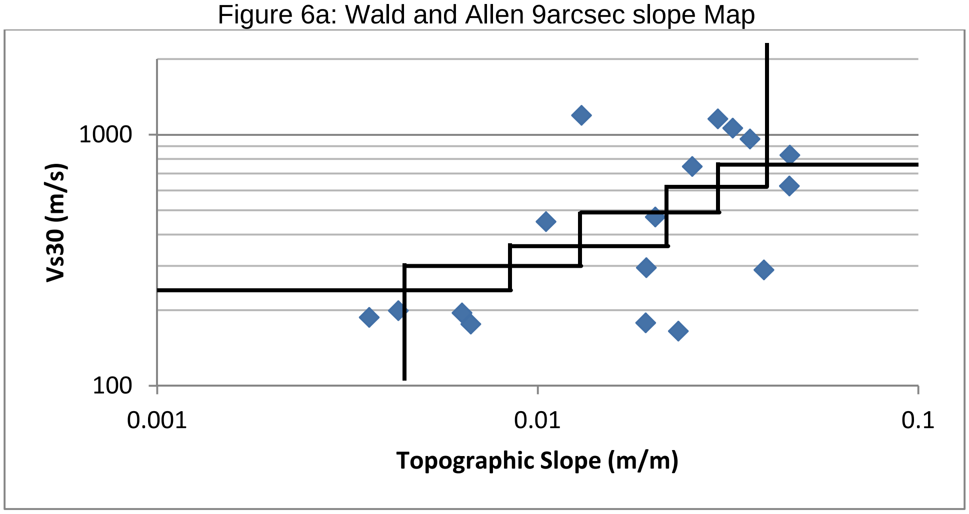

Figure 6b: V_{s30} versus 9 arcsec resolution topographic slope

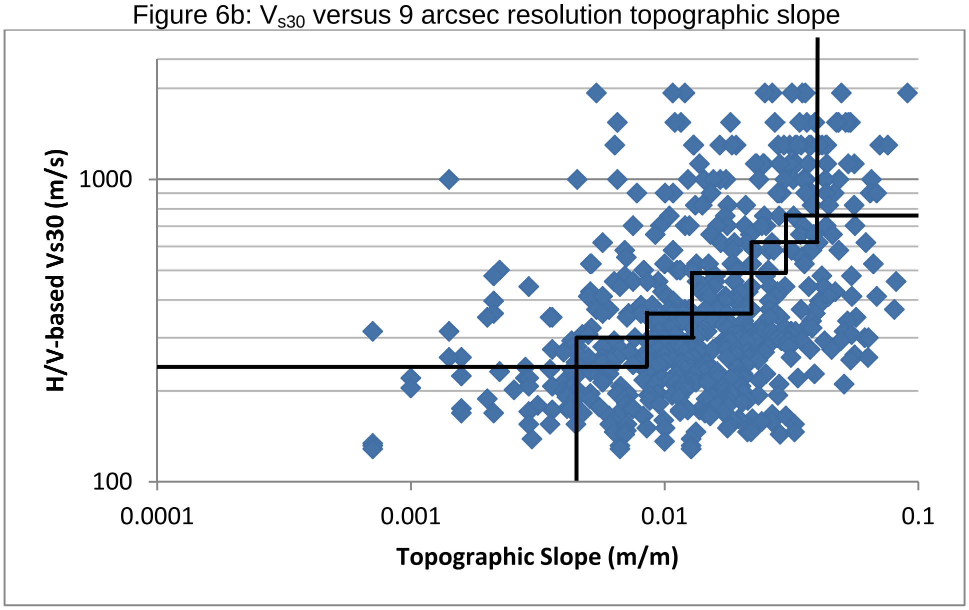

Figure 6c: H/V estimated V_{s30} versus 9 arcsec topographic slope

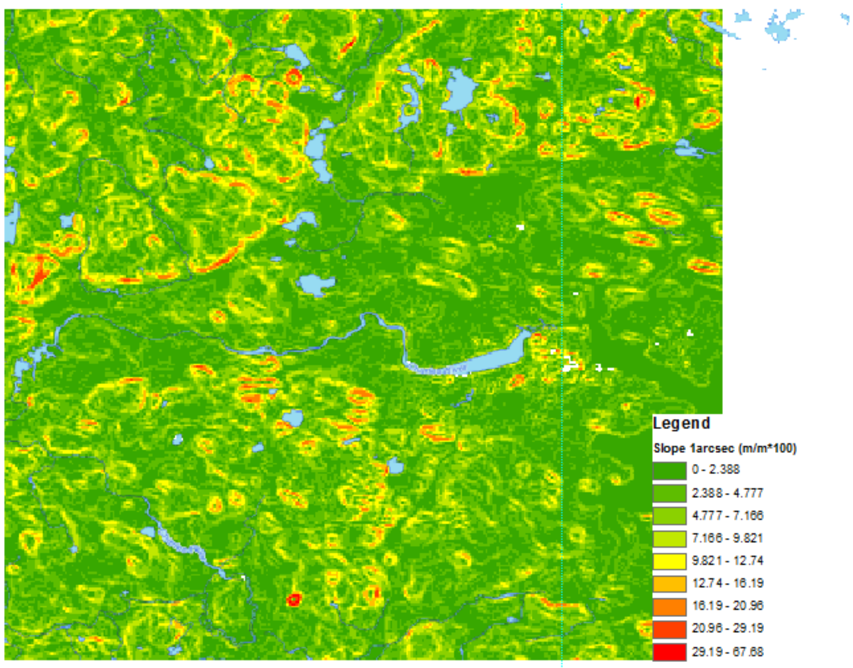

Figure 7a: Wald and Allen 3arcsec slope Map

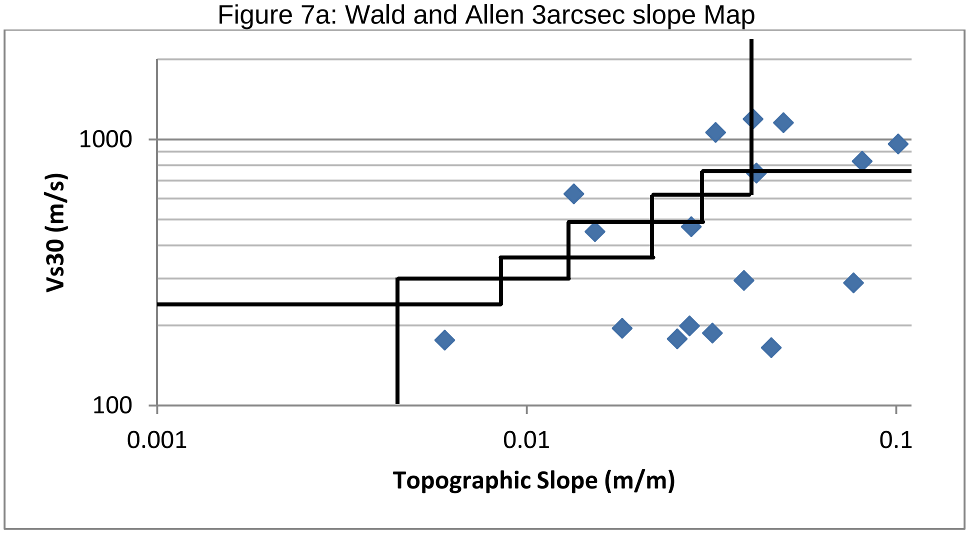

Figure 7b: V_{s30} versus 3 arcsec resolution topographic slope

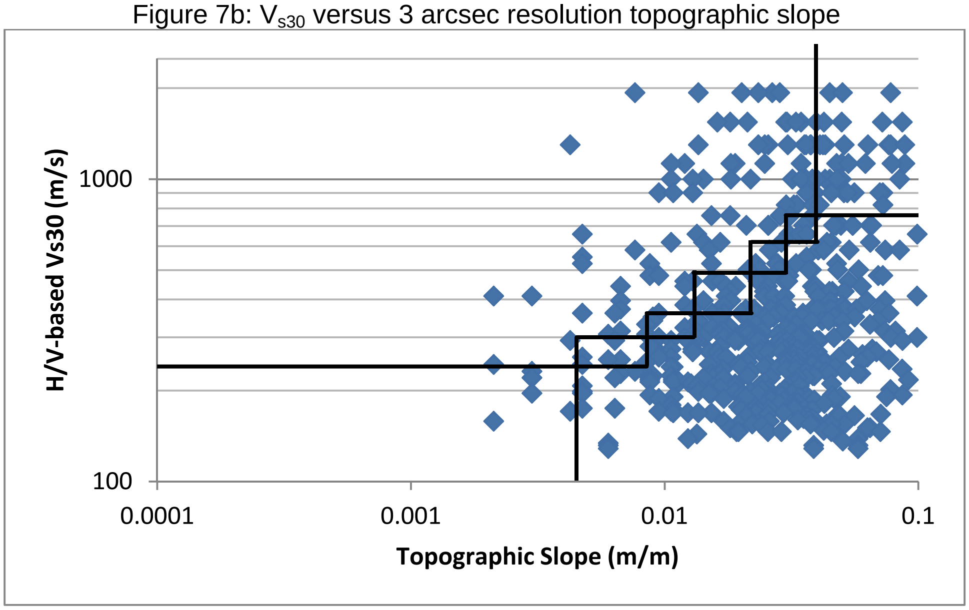

Figure 7c: H/V estimated V_{s30} versus 3 arcsec topographic slope

Table 4: Drumlin summary table of different V_{s30} methods

Longitude	Latitude	Station	Measured V_{s30} (m/s)	Measured V_{s30} Average	9 arcsec Slope-based V_{s30}	9 arcsec Slope-based Average V_{s30}	H/V Point	H/V Average
-71.1186	42.40702	903TUF	828	828	760	600	822	722

Table 5: Glaciofluvial summary table of different V_{s30} methods

Longitude	Latitude	Station	Measured V_{s30} (m/s)	Measured V_{s30} Average	9 arcsec slope-based V_{s30}	9 arcsec Slope-based Average V_{s30}	H/V Point	H/V Average
-71.1449	42.44048	905MVP	470		425		410	
-71.13772	42.39029	908DP	199		330		235	
-71.11013	42.32773	911JVA	1680		690		1298	
-71.18375	42.2803	919MIL	289	895	690	458	360	438
-71.06586	42.46197	923EPD	1859		210		268	
-71.18718	42.36804	926WAT	624		760		657	
-71.1982	42.34898	927NCP	450		330		425	

Table 6: Artificial Fill summary table of different V_{s30} methods

Longitude	Latitude	Station	Measured V_{s30} (m/s)	Measured Vs30 Average	9 arcsec slope-based V_{s30}	9 arcsec Slope-based Average V_{s30}	H/V Point	H/V Average
-71.1123	42.35435	909BUB	295		425		274	
-71.1315	42.36781	912SFR	195		270		179	
-71.0844	42.40442	918MAC	187		210		172	
-71.08126	42.39607	921ACM	452		425		220	
-71.0511	42.32452	924JMP	176		270		131	
-71.0467	42.30738	925MAL	165	199	555	374	193	238
-70.9642	42.44725	928LFP	174		270		220	
-71.0579	42.38457	931WTC	178		425		158	
-71.0268	42.36943	103EB	175		180		243	
-71.0474	42.34939	102SB	225		180		216	
-71.0907	42.3617	100MIT	225		180		258	

Table 7: Marsh Deposits summary table of different V_{s30} methods

Longitude	Latitude	Station	Measured V_{s30} (m/s)	Measured V_{s30} Average	9 arcsec slope-based Vs30	9 arcsec Slope-based Average V_{s30}	H/V Point	H/V Average
-71.1323	42.41353	902MVP	1004	1004	425	385	526	400

Table 8: Ground Moraine summary table of different V_{s30} methods

<table>
<tr><th>Longitude</th><th>Latitude</th><th>Station</th><th>Measured V_{s30} (m/s)</th><th>Measured V_{s30} Average</th><th>9 arcsec slope-based V_{s30}</th><th>9 arcsec Slope-based Average V_{s30}</th><th>H/V Point</th><th>H/V Average</th></tr>
<tr><td>-71.19569</td><td>42.3998</td><td>906RMC</td><td>1155</td><td rowspan="6">908</td><td>555</td><td rowspan="6">566</td><td></td><td rowspan="6">1123</td></tr>
<tr><td>-71.27363</td><td>42.50348</td><td>907BVA</td><td>747</td><td>555</td><td></td></tr>
<tr><td>-71.1379</td><td>42.3136</td><td>910LAP</td><td>1193</td><td>425</td><td>1298</td></tr>
<tr><td>-71.09047</td><td>42.30303</td><td>913FPZ</td><td>1061</td><td>690</td><td>1000</td></tr>
<tr><td>-71.08384</td><td>42.2698</td><td>920RPK</td><td>683</td><td>425</td><td>822</td></tr>
<tr><td>-71.03031</td><td>42.45873</td><td>922SQM</td><td>613</td><td>760</td><td>703</td></tr>
</table>

Table 9: Beach Deposits summary table of different V_{s30} methods

Longitude	Latitude	Station	Measured V_{s30} (m/s)	Measured V_{s30} Average	9 arcsec slope-based V_{s30}	9 arcsec Slope-based Average V_{s30}	H/V Point	H/V Average
-70.9893	42.41708	929WON	431	431	180	386	425	425

The glaciofluvial deposit has two points that are significantly higher than the others, as can be seen in Figure 8. These two stations, 911JVA and 923EPD, have V_{s30} profiles where the shear velocity suddenly increases, indicating shallow bedrock or glacial materials beneath a thin soil layer. 923EPD has the largest difference between H/V-based and measured V_{s30}. In the glaciofluvial deposits the slope-based average V_{s30} and the H/V-based V_{s30} average are in agreement, while the measured V_{s30} average is significantly higher due to stations 923EPD and 911JVA. The H/V estimates are closer to the individual measured V_{s30} values than the slope-based estimates. Removing 923EPD and 911JVA, the glaciofluvial deposits have a relatively consistent value. However, the stations 911JVA and 923EPD, with significantly higher V_{s30} values, show that the unit has the potential for large variations. This is most likely related to the fact that the glaciofluvial geologic unit ranges from thin to deep sediments over bedrock across the region.

The artificial fill geologic unit has a consistent V_{s30} value (Figure 9). The standard deviation of the average V_{s30} value is only 84 m/s. The artificial fill was typically placed on top of soft soils (such as Boston Blue Clay) along the coast and the major river channels in Boston. Both the artificial fill and the soft soils have low V_s values and the bedrock depth is generally greater than 30 m depth, which combine to make consistent V_{s30} value. The H/V-based V_{s30} values are very similar to measured V_{s30}. Slope-based V_{s30} values are consistently higher than the measured V_{s30}

values, making the average slope-based V_{s30} higher. The measured V_{s30} average and H/V-based V_{s30} average are close at 199.5 m/s and 235 m/s, respectively. The slope-based V_{s30} average, on the other hand, is 374 m/s.

The ground moraine has what appears as two sets of typical values for V_{s30} (Figure 10). One is just under 1200 m/s and the other is around 700 m/s. The two different values could be a result of the mixing of moraine material and bedrock into a single unit. The H/V-based V_{s30} values follow a similar pattern to the measured V_{s30} values. The slope-based correlation largely underestimates the values, with an average of about 568 m/s. The large difference in V_{s30} values in the ground moraine unit indicates an issue with estimating V_{s30} for an entire geologic unit, likely due to the heterogeneous nature of the unit.

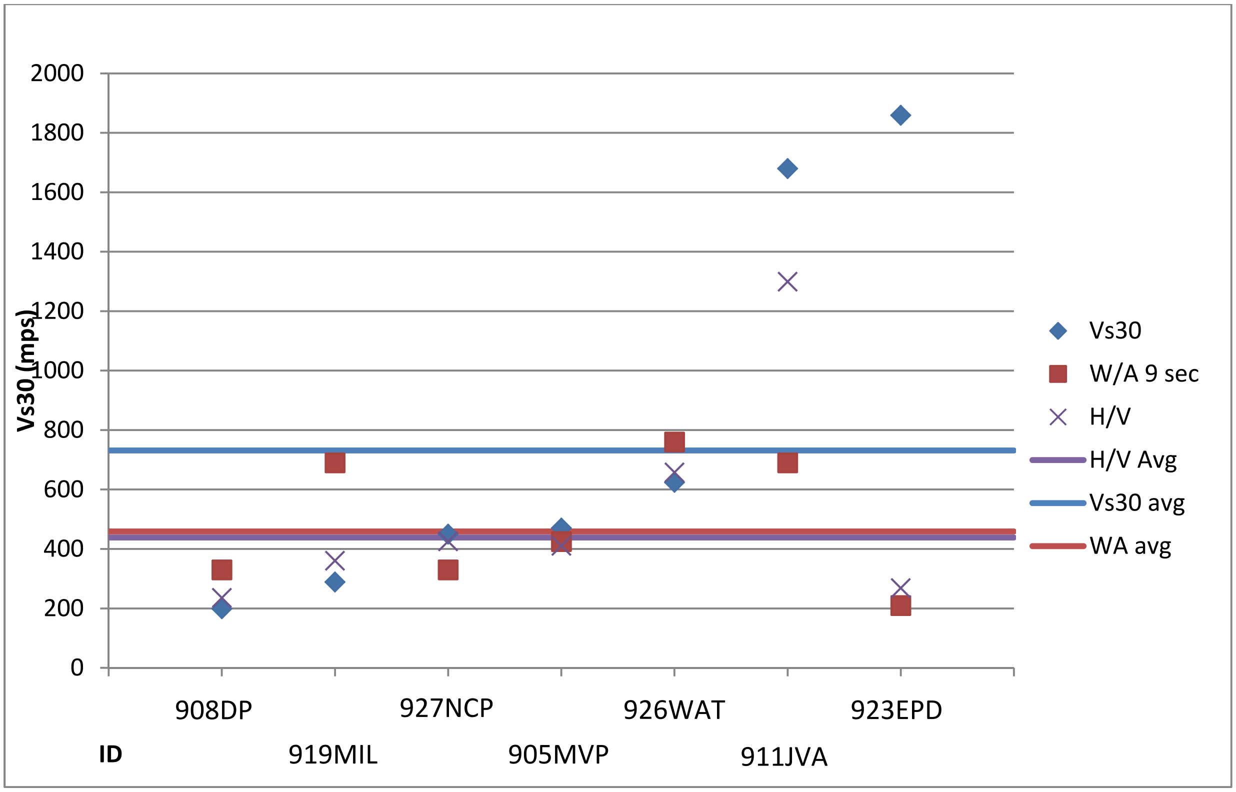

Figure 8: Method summary plot for glaciofluvial deposits surficial geology

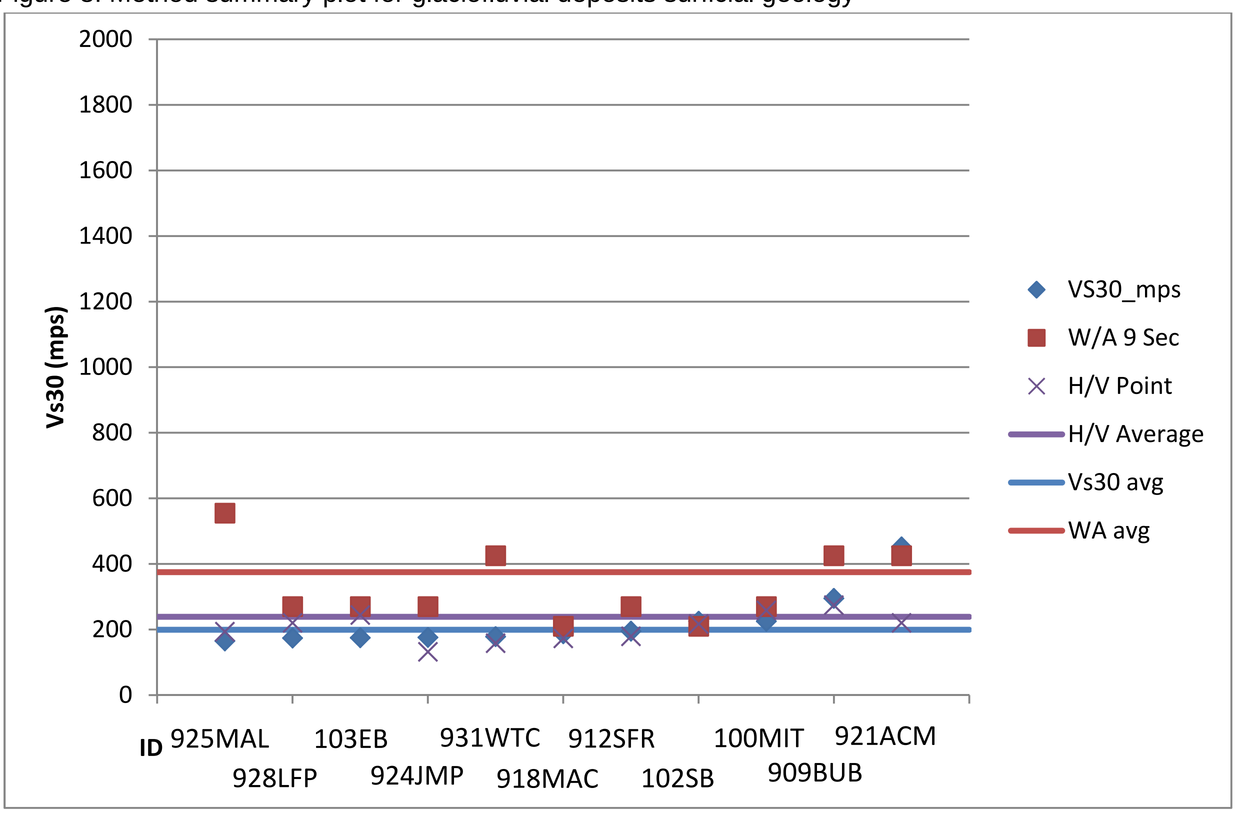

Figure 9: Method summary plot for artificial fill surficial geology

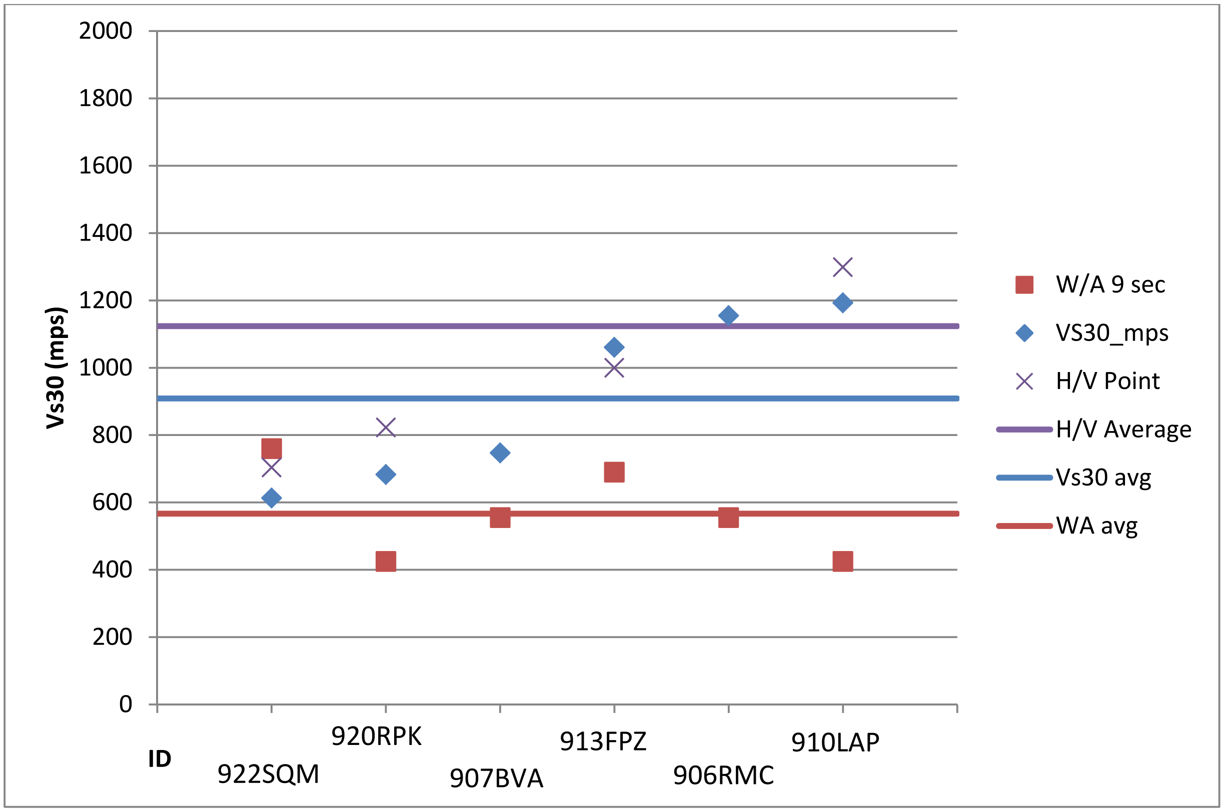

Figure 10: Method summary plot for Ground Moraine surficial geology

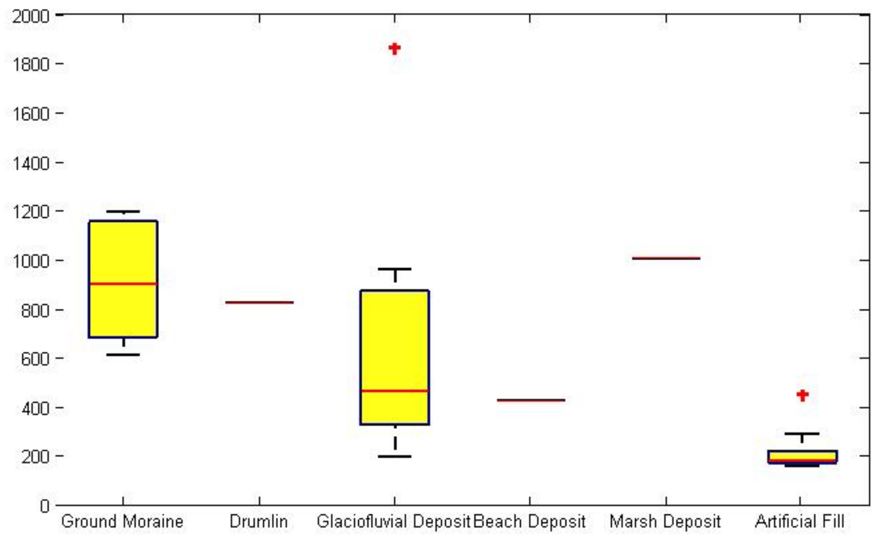

Figure 11: Box plots of V_{s30} data. Median (red bar), 1 standard deviation (yellow box), 2 standard deviations (black bar), and outliers (red crosses).

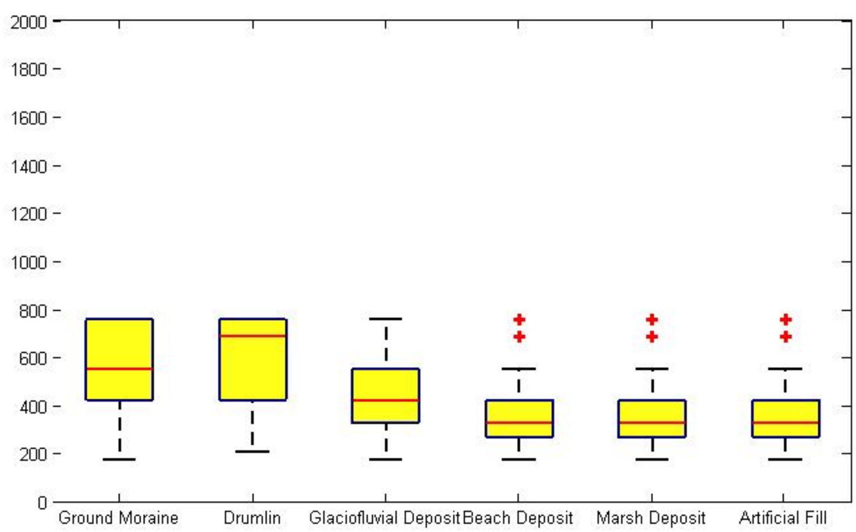

Figure 12: Box plots of slope-based V_{s30} estimates. Median (red bar), 1 standard deviation (yellow box), 2 standard deviations (black bar), and outliers (red crosses).

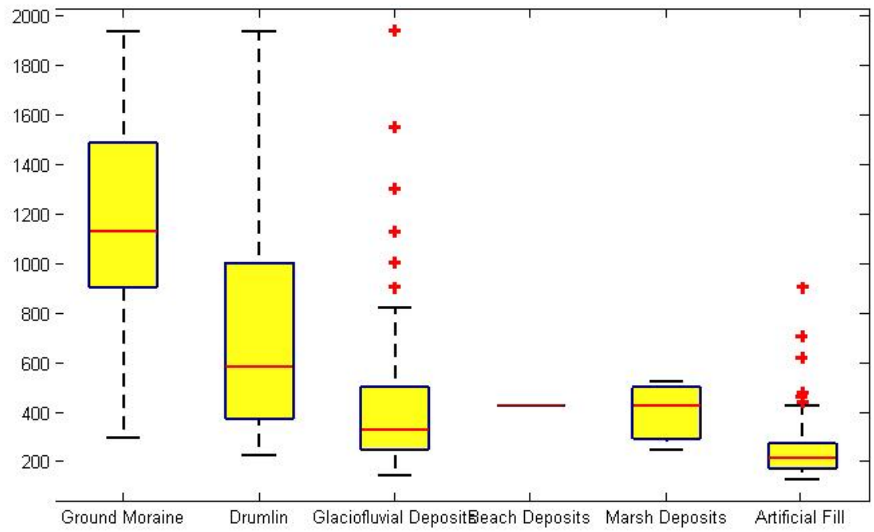

Figure 13: Box plots of H/V-based V_{s30} estimates. Median (red bar), 1 standard deviation (yellow box), 2 standard deviations (black bar), and outliers (red crosses).

The average H/V values of each geologic unit were applied to the surface geology units, as mapped in Figure 14. Now, at specific locations, an average value of V_{s30} can be determined for use in seismic design. The above mentioned issues within each geologic unit indicate the need for a more detailed geology map with a higher level of surficial geology classification.

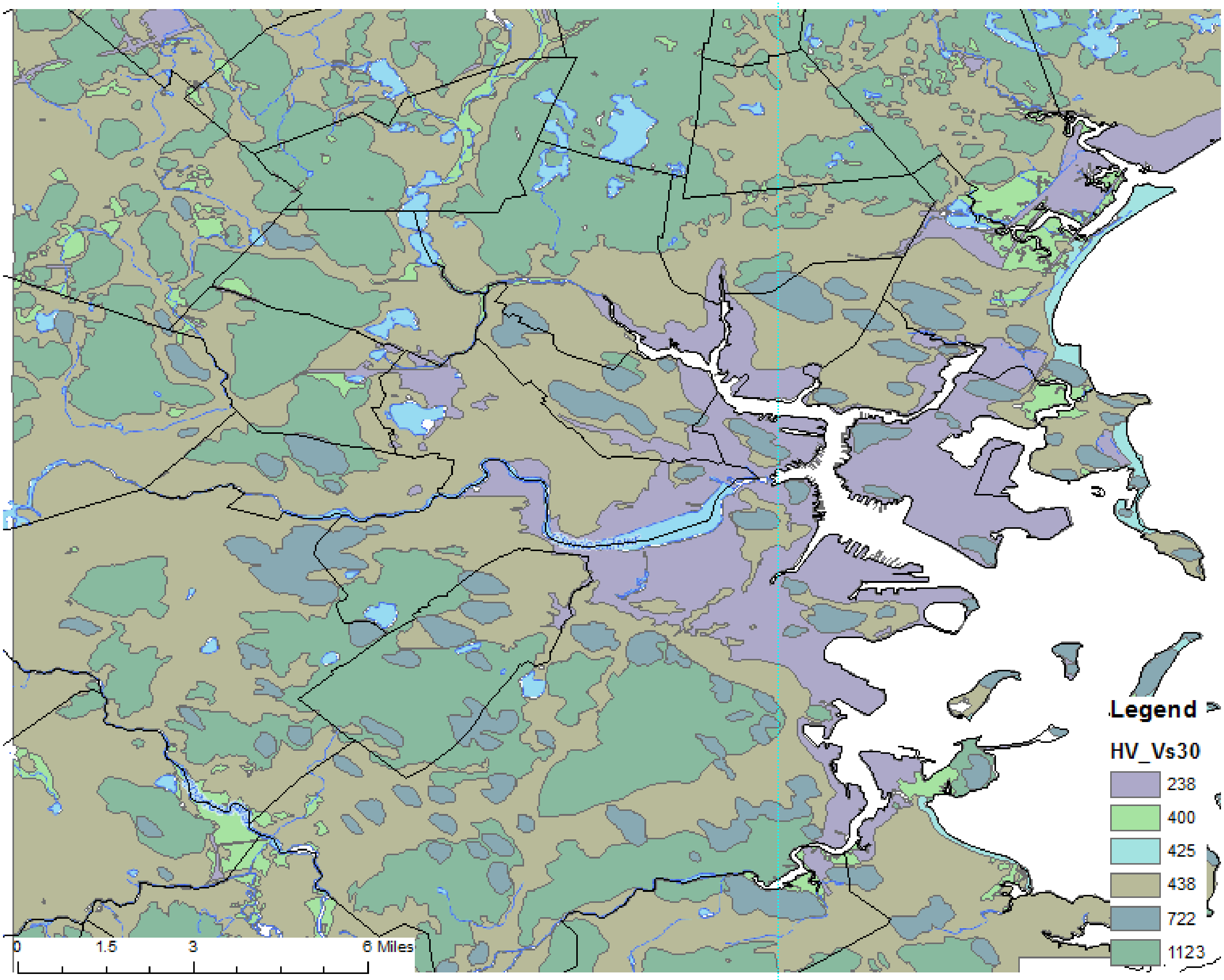

Figure 14: Map of average H/V-based V_{s30} in m/s

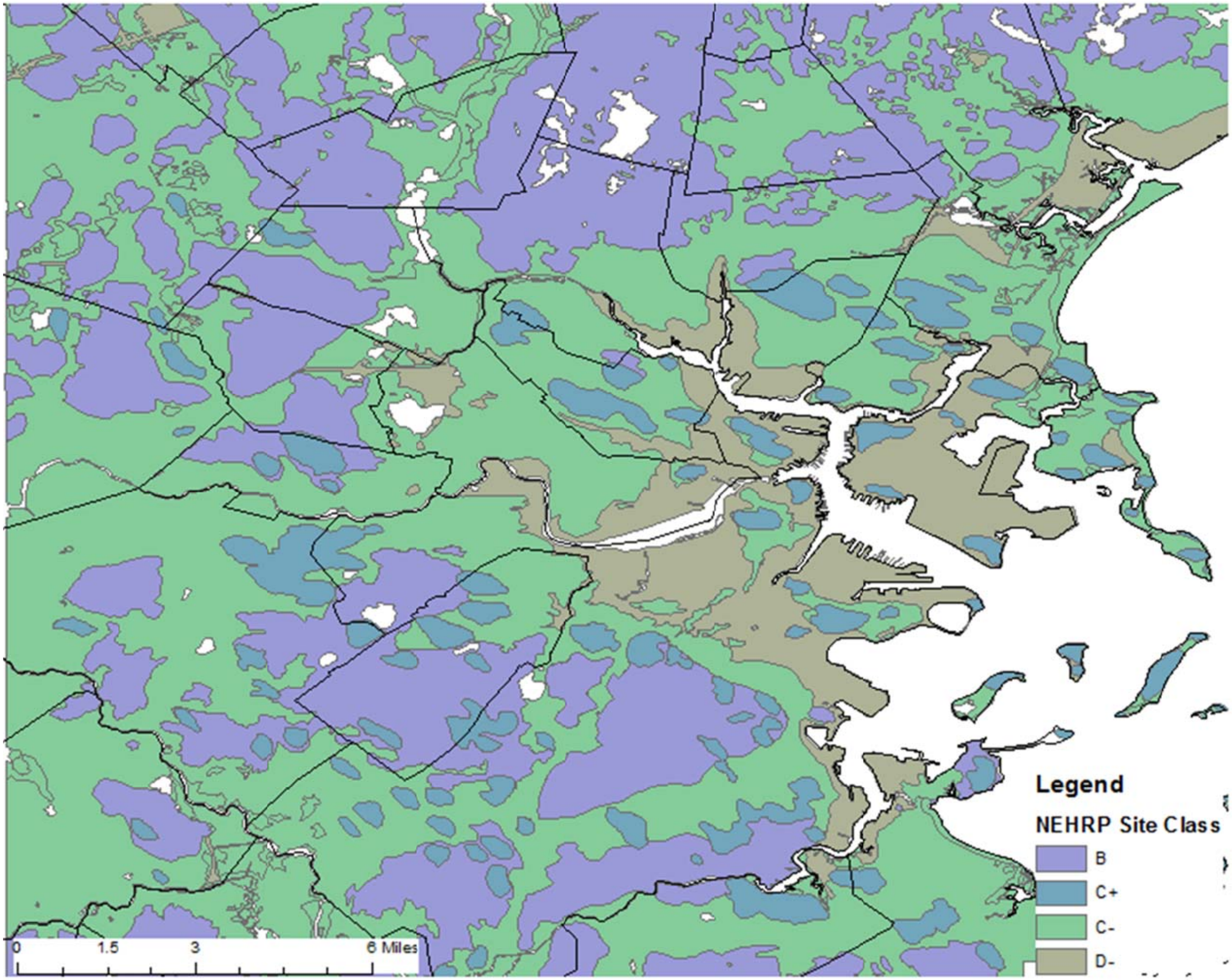

Figure 15: Map of H/V-based NEHRP Class

Conclusion

The Wald and Allen topographic slope-V_{s30} correlation method is appealing because it allows for determination of V_{s30} values using easily obtained topographic data. However, the correlation runs into a strong limitation with the actual accuracy at individual locations in Boston. In the Boston area, the topographic slope-based V_{s30} average values for each geologic unit fall within the Class C site class. This underestimates hard rock and overestimates loose soils and artificial soils. The Wald and Allen method is suitable for use only alongside a strong understanding of local geology. The local geologic knowledge will help designate the acceptability of the values. Two of the geologic units of focus, artificial fill, and ground moraine, have significantly different values between the topographic slope-based V_{s30} average and the H/V-based V_{s30} average. The glaciated terrain, with both high strength rock and poorly performing artificial fill, disrupts the Wald and Allen assumption relating ground slope, geologic processes of erosion and deposition, and soil strength.

Direct V_{s30} measurement remains the ideal for site specific values. To map locations that have not had V_{s30} measurements in Boston, averaging V_{s30} over geologic units becomes problematic because there are only 30 points available for the Boston area and only 27 of those points are within the surficial geology map. Three geologic units: drumlin, beach deposits, and marsh deposits, only have one V_{s30} measurement.

The other geologic units: glaciofluvial deposits, artificial fill, and ground moraine, have 7, 11, and 6 points respectively.

H/V measurements help alleviate this problem by having 560 measurements over a wide area. Here, a V_{s30} map was produced using the average H/V-based V_{s30} values for each geologic unit. Marsh and Beach only have 2 and 3 points, respectively, but also only designate a small area of the region. The consistency of the H/V-based V_{s30} values with measured V_{s30} validates its use as a correlation. Using an average has limitations that can be seen in the glaciofluvial and ground moraine geologic units. The glaciofluvial deposits have some locations with shallow sediments underlain by hard rock (ground moraine or bedrock), and therefore much higher V_{s30} values than thicker glaciofluvial deposits. The ground moraine geology was created by combining both ground moraines and bedrock as one unit. The combination may be the cause of two distinct average measured V_{s30} values. More detailed surficial geologic mapping, such as the Wills and Clahan (2006) paper that uses 19 geologic units in California, could help define the variation in V_{s30} by surficial geology. Adding units for shallow and deep glaciofluvial deposits and separating ground moraine and bedrock would help with the utility of the average values. Increasing the number of measured V_{s30} stations, especially in Marsh Deposits, Beach Deposits, and Drumlins would provide further correlation verification.

In the future, a more detailed surficial geology map that separates the six geologic units into more specific units could improve the use of V_{s30} proxies in Boston. More V_s measurements within the individual units would improve the analysis of the applicability of the H/V correlation. Basing the V_{s30} map on another parameter such as depth to bedrock or thickness of surficial geology could provide different results as well. H/V data is easily collectable due to easy set up costs and quick data collection. The ease of H/V data collection allows for large spatial coverage in a short period of time.

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Appendix – Definitions

V_s – is the abbreviated term for shear wave velocity. It is a measurement of the speed of which the S-wave moves through the medium at depth.

V_{s30} – is the average of the shear wave velocity in the top thirty meters

Microtremor – a microtremor is small ground vibrations cause by non-seismic events; such as trains, wave action, or cars.

H/V – is the ratio of the average horizontal acceleration to the vertical acceleration of the ground due to microtremors

Drumlin – a ground formation made up of poorly sorted clays, silts, sands, and gravels, often referred to as glacial till. They form hills due to the glacial deposition

Ground Moraine – ground moraines are made up of glacial till, poorly sorted clays, silts, sands, and gravels, but mostly flat

Glaciofluvial Deposits – glaciofluvial deposits are made up of the runoff from glacier melt

Marsh Deposits – are the deposits left from a marsh. The marsh deposits could be from either salt or fresh-water marshes.

Beach Deposits – are deposits left due to wave action. These deposits are continually being newly deposited or removed due to natural ocean behavior

Artificial Fill – is soils placed during construction to create or expand level ground. In Boston, un-engineered fill can be found under much of the historic buildings while engineered fill can be found under newer construction

Topographic Slope – is a measure of surface gradient. It was taken by using the adjacent 8 pixels to a point and calculating the change in m/m