Site Response in the eastern U.S.: A comparison of *Vs30* measurements with estimates from horizontal-to-vertical spectral ratios

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ABSTRACT

Earthquake damage is often increased due to local ground-motion amplification caused by soft soils, thick basin sediments, topographic effects, and liquefaction. A critical factor contributing to the assessment of seismic hazard is detailed information on local site response. In order to address and quantify the site response at seismograph stations in the eastern U.S (EUS), we investigate the regional spatial variation of horizontal-to-vertical spectral ratios (HVSR) using ambient noise recorded at permanent regional and national network stations as well as temporary seismic stations deployed in order to record aftershocks of the 2011 Mineral Virginia earthquake. We compare the HVSR peak frequency to surface measurements of the shear-wave seismic velocity to 30-m depth (*Vs30*) at 21 seismograph stations in the EUS and find that HVSR peak frequency increases with increasing *Vs30*. We use this relationship to estimate NEHRP soil class at 218 ANSS, GSN and RSN locations in the EUS and suggest that this seismic station based HVSR proxy could potentially be used to calibrate other site response characterization methods commonly used to estimate shaking hazard.

INTRODUCTION

The estimation of the earthquake hazard at a site depends on many factors including the distribution of the seismic source zones, the return times of large events, the predominant earthquake mechanisms near each site, the path effects of the transmitting medium (the earth), and local site effects on the seismic waves. Local site amplification for a single earthquake can vary significantly due to the presence of soft soils (Martin, 1994), thick basin sediments (Mundepi et al., 2009; Odum et al., 2010; Bodin and Horton, 1999; Pratt and Brocher, 2006), and topography (Toshinawa et al., 2004; Hartzell et al., 2014). Constraining the spatial variability of local site amplification is important in order to improve ground motion prediction equations (GMPE) used to develop the USGS national seismic hazard map (NSHM) (Petersen et al., 2008) and determine seismic provisions in building codes in the U.S. (Building Seismic Safety Council, 2009).

Compared to the western U.S. (WUS), earthquakes in the eastern U.S. (EUS) are less frequent but typically felt and cause damage over a much broader region due to efficient energy propagation (low attenuation) through the crystalline bedrock that underlies much of the EUS (Frankel et al., 1996; Benz et al., 1997). Though relatively infrequent, the EUS has experienced numerous earthquakes during historical time that have caused significant damage from ground shaking. Most recently, a moment magnitude (Mw) 5.8 earthquake occurred on August 23, 2011 (17:51:04 UTC) near Mineral, Virginia, (Figure 1) (McNamara et al., 2014a; Chapman 2013). The earthquake ruptured a southeast-dipping northeast-striking reverse fault within a region of diffuse seismicity known as the Central Virginia seismic zone (CVSZ) (Chapman, 2005; Algermissen and Perkins, 1976; Bollinger, 1969).

Ground shaking associated with the 2011 Mineral earthquake was felt (MMI$\geq$II) over a large region due to the relatively low attenuation (high *Q*) properties of the crust in the EUS (McNamara et al., 2014b). An estimated 10,000 people were exposed to moderate-to-heavy shaking levels (MMI=VIII) and 23,000 exposed to MMI=VI according to the USGS PAGER system (Wald et al*.,* 2010) (earthquake.usgs.gov/earthquakes/pager). Post-earthquake damage assessments found moderately heavy damage (MMI=VII-VIII) occurred to single and multi story homes and buildings in a rural area of Louisa County, southwest of Mineral, Virginia (Li, 2013; EERI, 2011) (Figure 1a). McNamara et al*.,* (2014b) showed that the contribution of both azimuthally dependent attenuation (1/*Q)* and local site amplification are required to explain the regional distribution of intensity observations, as well as the locally high shaking intensity observations (MMI V-VII) in specific areas such as Washington DC and coastal zones of the Northeast (Hough, 2012).

Multiple organizations deployed portable seismic stations in the days after the Mineral earthquake in order to record aftershocks (McNamara et al., 2014a). The combined seismic network that includes permanent USGS Advanced National Seismic System (ANSS), EarthScope Transportable Array (TA), regional seismic networks (RSN), and temporary portable seismic stations makes this aftershock sequence one of the best-recorded in the EUS (Figure 1) (Table 1). The abundance of aftershocks and local seismic stations presents new opportunities to better quantify EUS ground shaking parameters.

Given the recent emphasis on understanding earthquake hazards in the EUS following the

2011 Mineral, Virginia, earthquake, *Vs30* was measured at 66 portable and permanent seismic station locations in the CVSZ and greater EUS region (EPRI, 2012; Stephenson et al., this volume; R. Kayen, written communication). Based on numerous empirical studies (Borchert et al., 1976; Borcherdt, 1994; Wills and Silva, 1998), *Vs30* has become the most common means of classifying site conditions (soil class) and has been adopted in the National Earthquake Hazard Reduction Program (NEHRP) design provisions for new buildings (Martin, 1994). Since surface *Vs30* measurements are sparse, proxy methods are often used to estimate *Vs30* and soil class at most locations for USGS earthquake assessment and hazard products such as Shakemap and the NSHM.

In this paper, we investigate the potential for horizontal-to-vertical spectral ratios (HVSR) of ambient noise as a proxy for Vs30 estimate. We compute HVSR using ambient noise signal recorded at permanent and portable seismic stations in the EUS (Figure 1). We show a clear relationship between HVSR peak frequency and *Vs30* measured on the ground surface near seismic stations in the CVSZ (EPRI, 2012; Stephenson et al., this volume, Kayen, personal comm.). We then assume the CVSZ regional relationship between HVSR peak frequency and surface measurements of *Vs30* in order to estimate *Vs30* and soil class at 218 permanent seismic stations in the EUS. We suggest that this HVSR proxy could be used to calibrate topographic slope estimates of *Vs30* that are commonly used to estimate shaking hazard.

HVSR METHODS AND RESULTS

The premise of the HVSR method is that in shallow sedimentary deposits differences in the shear-wave impedance contrasts are larger than compressional-wave impedance changes. The underlying assumption is that when shear waves impinge on the boundary between bedrock and shallow sedimentary deposits, SV waves will convert to *P* waves and pass through the overlaying layer relatively unaltered while the SH waves will be strongly influenced by sedimentary layers (Nakamura, 1989). HVSR is generally considered to be a reliable measure of the primary resonance frequency but not to accurately determine local site amplification (Edwards et al*.*, 2013; Pratt and Brocher, 2006*;* Field et al*.*, 1995). Primary resonance frequency is an important parameter to determine because resonance may increase or amplify a building's response to ground shaking, especially if ground motions are at frequencies close or equal to the natural resonant frequency of the structure.

We use the spectral analysis system, PQLX (McNamara and Boaz, 2010) to compute all spectra used in our HVSR analysis. In this approach, the variation of spectral power is observed by computing instrument-corrected power spectral density (PSD) probability density functions (PDFs) after the methods of McNamara and Buland (2004). Percentile statistics derived from the PSDPDFs are used to estimate a smoothed distribution of spectral power as a function of frequency for each component of motion and to form the HVSR estimates.

In order to obtain the maximum number of possible HVSR estimates in the EUS, we use seismic stations equipped with instrumentation that records either weak or strong ground motion, however each requires different processing steps. For our HVSR analysis using weak-motion seismic stations, we are interested in isolating the ambient noise spectra from spectral transients due to earthquakes and recording system problems. We use the long term PSDPDFs to isolate the ambient noise spectra by trimming hourly

PSDs that fall outside of the 5th and 90th percentiles of the PDF. Figure 2 shows long-term PSDPDFs for weak-motion channels from the USGS portable aftershock station GS.SPFD (Figure 1, Table 1). The horizontal channel (BHE) PSDPDF shown in Figure 2a is constructed using 11,941 PSDs computed from hourly time segments overlapping by 50% that range from August 28, 2011 through March 21, 2012. Figure 2b shows the vertical channel (BHZ) long-term PSDPDF computed using 11,939 PSDs during the same time range. The long-term PSDPDF median (50%) spectra that is derived from weak-motion broadband seismometers, traverses the high probability, low power region of the PDFs and is comprised of ambient seismic noise. In contrast, PSDs that traverse the highest (>90%) and lowest power (<5%) regions of the PDFs are comprised of low-probability transients such as earthquakes and recording system problems (Figure 2) (McNamara et al., 2009).

After trimming transients, the remaining hourly PSDs are compiled into daily PSDPDFs. Daily PSDPDF medians are computed and used to form daily HVSRs (Figure 3a). We then compute the average of the daily HVSR estimates to form the weak-motion station HVSR (Sesame, 2004). Figure 3b shows the daily HVSR estimates computed from the ratio between the vertical component and the averaged horizontal components. A clear HVSR peak frequency is observed at 3-4 Hz for the portable station GS.SPFD while the HVSR estimate at US.BLA displays no significant ambient noise resonance frequency peaks. This method was applied to over 200 weak-motion stations in the EUS. Figure 4 shows some of the variability in weak-motion HVSR with peak frequencies in the range of 0.7 to 8.0 Hz observed at several seismic stations in this study.

A difficulty in estimating HVSR using strong motion sensors is that they are insensitive to low-power ambient noise levels commonly used to compute HVSRs. In order to include strong-motion sensors in this HVSR study we are required to use the low-probability high-power portion of the PSDPDF that is comprised of earthquake signals. As noted earlier, high power PSDs observed in the PSDPDFs, such as the 95th percentile, represent the very highest power signals from earthquakes such as the 2011 Mineral, VA earthquake and larger aftershocks. Both weak and strong motion instruments were operating at several stations in this study (GS.SPFD, US.BLA, and US.CBN) and offer the ability to compare results. Figure 5 shows HVSR estimates formed using daily strong-motion PDFPDF 95th percentiles with average HVSR results computed from the weak motion records. The HVSR peak frequency and amplitude are nearly identical, suggesting that both the median and 95th percentile of the PSDPDF can be used to estimate HVSR.

HVSR Results

After forming the individual station HVSRs we visually inspect the results for both clear peaks and the absence of clear peaks on both the weak and strong motion stations. For stations with clear peaks, we manually pick the peak frequency on the average HVSR estimates and the 2σ standard deviations in order to determine the pick uncertainty (Table 1). Stations with no clear HVSR peak are considered to have no result and labeled NR in Table 1 (see US.BLA in Figures 3 and 5).

The results shown in Figures 3 through 5 demonstrate the variability in HVSR peak frequency and amplification factor observed at several seismic stations in the EUS.

The resonance frequency (*f*) of a site is related to the thickness (*h*) and the average *S-wave* velocity (*Vs*) of the softer geologic material near the surface (Lermo and Chavez-Garcia, 1993; Lachet and Bard, 1994; Castellaro and Mulargia, 2009) where: $f=Vs/4h$ (Bard, 1999). For example, US.BLA is installed in a vault excavated into bedrock and shows no significant ambient noise resonance frequency peaks (NR: Figures 1 and 3b). The lack of an HVSR peak indicates that no significant impedance contrast exists below the surface. In contrast, the temporary aftershock station GS.SPFD was installed in a shallow vault in loosely consolidated saprolite and soils (Stolt et al., 1991) and shows clear HVSR peak at 3 Hz (Figure 3b). In general, we observe a broad range of resonance peaks, from 0.2-10Hz, with variable width and amplification (Figure 4).

DISCUSSION

Vs30. Understanding the spatial variability of site response is important to hazard mitigation (Boore, 2004). Modern GMPEs utilize site amplification factors based on broad soil classes that are most commonly defined by the average shear-wave velocity in the upper 30 m (*Vs30*) (Martin, 1994; Borcherdt, 1994; Wills and Silva, 1998). High *Vs30* values are associated with firm, dense rock and lower levels of ground shaking while lower *Vs30* values are associated with softer soils and site amplification on the order of 1.5-2 (Petersen et al., 2008).

Vs30 is commonly computed from surface measurements of *Vs* using a receiver array and either using active sources, or passive ambient noise microtremor sources (Odum et al., 2010; Odum et al., 2013; Stephenson et al., this volume). Following the

2011 Mineral earthquake, *Vs30* was measured at the locations of 66 portable and permanent seismic stations in the CVSZ and greater EUS (EPRI, 2012; Stephenson et al., this volume; Kayen, personal comm.) (Table 2). This data set of surface *Vs30* measurements provides a valuable resource for comparison of proxy methods used to estimate *Vs30* and soil class.

In Figure 6 we compare surface measured *Vs30* at 21 seismic station locations with clear observations of HVSR peak frequency. A least-squares regression between HVSR peak frequency and *Vs30* measured at the surface results in a slope of m=51.90$\pm$65.95 and intercept of b=254.73+28.52 with a data standard deviation = *78.91* m/s (Figure 6). The relatively low standard deviation and high data cross correlation coefficient of 0.89 suggests a clear relationship between HVSR peak frequency and surface measurements of *Vs30*.

Since surface *Vs30* measurements are not available at all site locations of interest for earthquake hazard assessment (Petersen et al., 2008), a common method used to estimate *Vs30* takes advantage of topographic slope (Allen and Wald, 2007; 2009). For each location of the 66 seismic stations with surface measurements of *Vs30* we extract the topographic slope proxy *Vs30* from the USGS Global *Vs30* Map Server (http://earthquake.usgs.gov/hazards/apps/vs30/). As a test we compare how well our HVSR peak frequency proxy relationship compares with the topographic slope proxy at predicting *Vs30* measured at the surface. Figure 7 compares 66 surface measurements of *Vs30* to topographic slope proxy *Vs30*. A least-squares regression results in a slope of 0.173+0.065 and intercept of 368.79+42.25 (data standard deviation = 155.79 m/s, data cross correlation coefficient = 0.31). The large standard deviation and low cross correlation coefficient indicates that the topographic slope proxy is not a reliable predictor of *Vs30* measured at the surface for this data set. The topographic slope proxy estimate tends to underestimate *Vs30* measured at the surface.

In figure 7 we also determine how well our HVSR peak frequency proxy relationship predicts *Vs30* measured at the surface. We estimate *Vs30* at 21 seismic stations with clear HVSR peak frequencies and co-located surface measurements of *Vs30*. A least-squares fit between surface measured *Vs30* and HVSR proxy *Vs30* results in a slope of $m=0.783+0.090$ and intercept $b=99.24+43.59$ (data standard deviation = 69.76 m/s, data cross correlation coefficient = 0.89). The relatively low standard deviation and high data cross correlation coefficient indicates that HVSR peak frequency can reliably estimate *Vs30* measured at the surface for this CVSZ dataset.

Soil Class

The 218 seismic stations used in this study are installed in a broad range of soils and consequently result in a range of HVSR peak frequencies (Figures 3, 4 and 5). Figure 6 shows the NEHRP soil class boundaries, defined by *Vs30* (Martin, 1994), and the linear relationship observed between HVSR peak frequency and surface measurements of *Vs30*. If we assume that the empirical linear relationship defines a proxy relationship, we can estimate *Vs30* and thereby infer NEHRP soil class for seismic stations with a clear HVSR peak frequency.

In Figure 1 we map the distribution of soil class estimates at 218 seismic stations using the HVSR proxy determined in this study (Table 1). Seismic stations used in this study are located in both solid rock (e.g., US.BLA: http://earthquake.usgs.gov/monitoring/operations/station.php?network=US&station=BLA

) and in highly weathered and saturated soils such as near the North Anna reservoir and nuclear power plant (GS.ORRD, GS.SPRD) (Figure 1). We observe that most stations are located in soil class C (very dense soil and soft rock), CD and D (stiff soil) (Martin, 1994). Soil class D estimates are most commonly associated with in areas of thick sediments such as southeast coastal areas of Virginia, the Carolinas and Florida, the Michigan basin, and the Mississippi embayment sediments. Soil class C and HVSR measurements with no clear peak (NR) are common in the higher elevation regions of the Appalachian Mountains. Based on this analysis we see that much of the EUS has local site conditions that can significantly amplify ground motions.

The geology of EUS is marked by a wide variety of provinces, from the eastern coastal plains westward to the Appalachian plateau. The epicentral region of the 2011 Mineral, VA earthquake is located within the Piedmont Province and is characterized by gently rolling topography, deeply weathered bedrock, and a relative paucity of solid rock outcrop. Saprolite is the most common near-surface material in the Piedmont region of Virginia (Stolt et al., 1991) and is generally formed in place as gradationally weathered material from the underlying bedrock. Saprolites are also common in other regions, such as Hong Kong, where strong motion site response studies have shown that thin layers of saprolite (*Vs30* = 100-400 m/s) overlying high velocity bedrock (*Vs30* = 1500 m/s) can lead to significant local site amplification (Pappin et al., 2004; Koo et al., 2005). In addition, thicker layers of saprolite (~22m) that overlay very high velocity bedrock (*Vs*=2400m/s) at sites near Mayaguez, Puerto Rico have been shown to have very large local site amplification (Odum et al., 2013). *Vs30* for saprolite in the 2011 Mineral, VA earthquake epicentral ranges from 200 to 400 m/s (Stephenson et al., this volume) which is consistent with soils of class C and D. Similar to other regions, saprolite with soil class of C and D within the EUS can be expected to produce significant site amplification (Figure 1).

Implications for Structures

The characteristics of ground motion that are most important for building design are the duration, amplitude, and frequency of horizontal ground motion. In this study we demonstrate that HVSR peak frequency can be used as a proxy to estimate *Vs30* and consequently NEHRP soil class, which are the dominant parameters used to determine local site amplification. The 2011 Mineral, Virginia earthquake produced shaking sufficient to close the North Anna nuclear power plant, located ~20 km from the epicenter, with reported shaking levels reaching a factor of two times the maximum design limit (Li, 2013; EERI, 2011). Recorded peak ground acceleration (PGA) reached 2.6 cm/s^2 (Li, 2013; Chapman, 2013) and is consistent with the USGS PAGER intensity model (MMI=VI-VII) (Figure 1a) and with post-event damage assessment (EERI, 2011). As observed in Figure 1a, seismic stations located in the epicentral region of the 2011 Mineral earthquake and near the North Anna Power Plant are of soil class C and D which can expected to significantly amplify ground shaking (Petersen et al., 2008).

Also of great importance in building design is the frequency of horizontal ground motion. When the frequency content of ground motion is near a building's natural frequency, the building and the ground motion are in resonance with one another. Based on the conventional relationship in which the resonance period (1/frequency) is 0.1 * number of stories, we can estimate building heights that are most sensitive to the resonance frequency of the soils in this study. For example, a 20-story building is likely most sensitive to soils with resonant frequency of 0.5 Hz (2.0s period) similar to the observation at US.CBN (Figure 4), whereas a 10-story building is sensitive to soils with a resonant frequency of 1.0 Hz (1s period) similar to stations near the North Anna power plant (Table 1). The highest HVSR peak frequencies observed for soils in this study (ET.SWET, GS.OORD) (~10 Hz) suggest that single story buildings are also at risk. The wide range of resonant frequency observations are consistent with the broad range of building damage observed in the epicentral region immediately following the mainshock (EERI, 2011).

Limitations and Uncertainty

Though the distribution of our soil class estimates is generally consistent with regional geology, individual station results can be difficult to interpret. This is the case for stations labeled "NR" that do not have a clear peak frequency. If a seismic station is part of a permanent seismic network, most likely the station is not sensitive to the local shallow soil. Most permanent earthquake monitoring stations are built to reduce noise by placing sensors on concrete piers coupled directly to bedrock or in borehole installations (McNamara et al., 2009). As demonstrated with IU.DWPF in Figure 4, deeply buried sensors do not record site effects because they lie below the shallow soils. Based on the peak HVSR resonance frequency observed with the surface sensor at IU.DWPF.10 (1Hz), the surface soils should have a *Vs30*=316 m/s and soil class of D (Figure 6). In contrast, the borehole sensor (IU.DWPF.00) has no HVSR peak frequency since it is coupled to solid rock at depth of 162 m (Figure 4). Many of the permanent ANSS, GSN and USArray TA stations have no HVSR peak frequency (Table 1) (Figure 1b). Sensors buried at shallow depth, such as those used in portable or temporary aftershock networks, are often better for determining high-frequency soil characteristics. This contrasts with the permanent ANSS station US.CBN which has a clearly observed HVSR peak frequency of ~0.7Hz (Figure 4) due to installation in thick class D soil (Table 1) (Kayen, personal comm.) (http://earthquake.usgs.gov/monitoring/operations/station.php?network=US&station=CBN) . Based on the regression results shown in Figure 6, we estimate *Vs30* = 302 m/s,

Since the paucity of local observations limits our ability to adequately evaluate near-field strong ground motion we require proxy methods to estimate site response for most locations. It is possible that the linear relationship between *Vs30* and HVSR peak frequency, determined in this study, is unique to the 21 stations located in the CVSZ may not be an appropriate *Vs30* proxy for the entire EUS and other regions. Therefore we recommend that results from this study be compared to different regions where surface *Vs30* measurements are available for existing seismic stations. Since surface measurements of *Vs30* are spatially limited, we also recommend additional measurement of *Vs30* at existing seismic stations.

CONCLUSIONS

In this study, we compute HVSR peak frequency for 218 seismic stations in the EUS. The surface measured *Vs30* data set collected after the 2011 Mineral, Virginia earthquake provides an opportunity to compare these observations with the HVSR results at the same locations. We show a strong linear relationship between HVSR peak frequency and surface *Vs30* measurements in the CVSZ and suggest that this approach can be used as a proxy to estimate *Vs30* and NEHRP soil class in the EUS. For stations in this study, the HVSR *Vs30* proxy is more reliable at predicting surface measured *Vs30* than *the* topographic slope proxy. Since surface measurements of *Vs30* are spatially limited we suggest that our approach can be used where seismic stations are available in order to calibrate topographic slope estimates of *Vs30* that are commonly used to estimate shaking hazard. Local soil class is a significant issue for the construction of buildings and other structures, and is commonly used by engineers in the development of building design criteria. Based on our results it is important to quantify local soil class in order to provide guidance on the design of buildings and infrastructure in regions that can experience strong ground shaking. Studies of this nature are also relevant to rapid USGS earthquake assessment and hazard products that are important for the improvement of building codes in the EUS.

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TABLES

TABLE 1. SOIL CHARACTERISTICS
AT 218 SEISMIC STATIONS IN THE EUS

NET.STATION	HVSR Peak Frequency (Hz)	HVSR Vs30 (m/s)	NEHRP Soil Class
AG.CCAR	0.65	288.3	D
AG.FCAR	5.0	513.7	C
AG.HHAR	NR	NR	NR
AG.LCAR	20	1290.7	B
AG.WHAR	NR	NR	NR
AG.WLAR	0.35	272.8	D
CN.PLVO	NR	NR	NR
CN.SADO	NR	NR	NR
CO.JSC	NR	NR	NR
ET.CPCT	NR	NR	NR
ET.SWET	10.0	772.7	BC
GS.CVRD	2.5	384.2	CD
GS.LWRD	2.25	371.2	CD
GS.ORRD	8.0	669.1	C
GS.PTRD	1.5	332.4	D
GS.SPFD	3.0	410.1	CD
GS.SPRD	4.0	461.9	C
IM.TKL	NR	NR	NR
IU.DWPF	1.4	327.2	D
IU.HRV	NR	NR	NR
IU.SSPA	NR	NR	NR
IU.WCI	NR	NR	NR
IU.WVT	8.5	695	C
LD.ALLY	NR	NR	NR
LD.FRNY	NR	NR	NR
LD.KSCT	NR	NR	NR
LD.LUPA	NR	NR	NR
LD.MVL	10	772.7	BC
LD.NCB	NR	NR	NR
LD.PAL	NR	NR	NR
LD.SDMD	NR	NR	NR
NE.BCX	NR	NR	NR
NE.BRYW	NR	NR	NR
NE.EMMW	NR	NR	NR
NE.FFD	1.5	332.4	D
NE.HNH	NR	NR	NR
NE.QUA2	NR	NR	NR
NE.TRY	0.5	280.6	D
NE.VT1	3.5	436	C
NE.WES	NR	NR	NR
NE.WSPT	NR	NR	NR
NE.YLE	NR	NR	NR
NM.BLO	NR	NR	NR
NM.GLAT	0.2	265.0	D
NM.HALT	0.25	267.6	D
NM.HBAR	0.25	267.6	D
NM.MGMO	8.0	669.1	C
NM.MPH	0.18	264.0	D
NM.OLIL	2.5	384.2	CD
NM.PARM	0.4	275.4	D
NM.PBMO	3.5	436	C
NM.PLAL	3.5	436	C
NM.PVMO	0.25	267.6	D
NM.SLM	NR	NR	NR
NM.UALR	NR	NR	NR
NM.USIN	9.0	720.9	C
NM.UTMT	0.35	272.83	D

NP.9985	1.6	337.58	D
NQ.WNC	NR	NR	NR
PE.NCAT	4.5	487.8	C
PE.PAGS	5.0	513.7	C
PE.PSUB	NR	NR	NR
TA.059A	NR	NR	NR
TA.060A	0.45	278.01	D
TA.061Z	NR	NR	NR
TA.147A	NR	NR	NR
TA.152A	2.5	384.2	CD
TA.154A	0.3	270.24	D
TA.250A	0.25	267.65	D
TA.253A	0.9	301.32	D
TA.255A	1.1	311.68	D
TA.257A	1.5	332.4	D
TA.352A	1.0	306.5	D
TA.451A	2.0	358.3	D
TA.453A	1.5	332.4	D
TA.456A	1.0	306.5	D
TA.555A	4.0	461.9	C
TA.656A	3.0	410.1	CD
TA.658A	2.2	368.66	CD
TA.957A	1.5	332.4	D
TA.C40A	NR	NR	NR
TA.D41A	NR	NR	NR
TA.D53A	NR	NR	NR
TA.E38A	2.0	358.3	D
TA.E43A	11	824.5	B
TA.E44A	NR	NR	NR
TA.E46A	NR	NR	NR
TA.G40A	2.5	384.2	CD
TA.G45A	NR	NR	NR
TA.H43A	NR	NR	NR
TA.H48A	1.0	306.5	D
TA.I41A	NR	NR	NR
TA.I42A	NR	NR	NR
TA.I45A	0.7	290.9	D
TA.I47A	1.5	332.4	D
TA.I49A	6.0	565.5	C
TA.J45A	0.8	296.1	D
TA.J47A	1.2	316.8	D
TA.J48A	4.5	487.8	C
TA.J54A	3.9	456.7	C
TA.J55A	5.5	539.6	C
TA.K43A	NR	NR	NR
TA.K50A	1.5	332.4	D
TA.KMSC	4.0	461.9	C
TA.L40A	6.5	591.4	C
TA.L42A	5.5	539.6	C
TA.L46A	1.2	316.8	D
TA.M44A	6.0	565.5	C
TA.M46A	1.4	327.2	D
TA.M48A	1.3	322.0	D
TA.M50A	2.5	384.2	CD
TA.M52A	5.5	539.6	C
TA.M54A	2.5	384.2	CD
TA.M55A	NR	NR	NR
TA.M65A	0.85	298.7	D
TA.N41A	5.5	539.6	C
TA.N47A	2.5	384.2	CD
TA.N49A	NR	NR	NR
TA.N51A	4.0	461.9	C
TA.N53A	NR	NR	NR
TA.N54A	NR	NR	NR
TA.N55A	NR	NR	NR
TA.N59A	NR	NR	NR
TA.O49A	6.0	565.5	C

TA.O52A	4.5	487.8	C
TA.O56A	NR	NR	NR
TA.P45A	3.0	410.1	CD
TA.P48A	4.2	472.2	C
TA.P51A	1.5	332.4	D
TA.P53A	NR	NR	NR
TA.Q51A	3.0	410.1	CD
TA.Q54A	NR	NR	NR
TA.R49A	NR	NR	NR
TA.R50A	NR	NR	NR
TA.R53A	2.0	358.3	D
TA.R55A	NR	NR	NR
TA.R58B	3.5	436	C
TA.S51A	NR	NR	NR
TA.S57A	3.5	436	C
TA.S58A	NR	NR	NR
TA.SFIN	0.9	301.32	D
TA.SPMN	2.0	358.3	D
TA.T45A	0.75	293.5	D
TA.T47A	6.5	591.4	C
TA.T49A	3.5	436	C
TA.T52A	8.0	669.1	C
TA.T57A	3.8	451.54	C
TA.T59A	7.0	617.3	C
TA.T60A	0.35	272.83	D
TA.TIGA	1.5	332.4	D
TA.TUL1	NR	NR	NR
TA.U40A	2.5	384.2	CD
TA.U54A	1.5	332.4	D
TA.U59A	2.1	363.4	C
TA.V48A	7.0	617.3	C
TA.V51A	NR	NR	NR
TA.V52A	NR	NR	NR
TA.V53A	6.0	565.5	C
TA.V55A	NR	NR	NR
TA.V56A	NR	NR	NR
TA.V60A	0.6	285.7	D
TA.V61A	0.2	265.0	D
TA.W39A	NR	NR	NR
TA.W41B	NR	NR	NR
TA.W50A	7.8	658.7	C
TA.W52A	1.9	353.1	D
TA.W57A	4.5	487.8	C
TA.WHTX	NR	NR	NR
TA.X40A	NR	NR	NR
TA.X43A	NR	NR	NR
TA.X48A	11	824.5	B
TA.X51A	3.0	410.1	CD
TA.X58A	0.8	296.1	D
TA.Y49A	NR	NR	NR
TA.Y52A	NR	NR	NR
TA.Y57A	1.1	311.6	D
TA.Y58A	0.4	275.4	D
TA.Y60A	4.0	461.9	C
TA.Z41A	NR	NR	NR
TA.Z50A	3.2	420.4	C
TA.Z56A	0.5	280.6	D
US.AAM	1.4	327.2	D
US.ACSO	3.0	410.1	CD
US.AGMN	1.5	332.4	D
US.BINY	NR	NR	NR
US.BLA	NR	NR	NR
US.BRAL	1.4	327.2	D
US.CBN	0.7	290.9	D
US.CNNC	0.9	301.3	D
US.COWI	2.4	379.0	CD
US.ERPA	NR	NR	NR

US.EYMN	NR	NR	NR
US.GOGA	NR	NR	NR
US.HDIL	0.9	301.3	D
US.JFWS	NR	NR	NR
US.LBNH	NR	NR	NR
US.LONY	NR	NR	NR
US.LRAL	2.5	384.2	CD
US.MCWV	NR	NR	NR
US.MIAR	NR	NR	NR
US.NATX	NR	NR	NR
US.NHSC	4.5	487.8	C
US.OXF	0.4	275.4	D
US.PKME	NR	NR	NR
US.SCIA	1.1	311.6	D
US.TZTN	NR	NR	NR
US.VBMS	1.7	342.7	D
YC.IP01	4.5	487.8	C
YC.IP02	2.5	384.2	CD
YC.IP03	4.0	461.9	C
YC.IP04	4.0	461.9	C
YC.IP05	2.75	397.1	CD
YC.IP06	5.0	513.7	C
YC.IP07	2.3	373.8	CD
ET.UOM1	9.0	720.9	C
ET.UOM2	2.5	384.2	CD
XY.BUPP	2.7	394.5	CD
NM.SIUC	5.5	539.6	C

TABLE 2. Vs30 OBSERVATIONS
AT 66 SEISMIC STATIONS IN THE EUS

NET.STATION	Surface Vs30 (m/s)	Topo Vs30 (m/s)
GS.ORRD	544.0	406.9
GS.SPRD	580.0	356.6
YC.IP01	530.0	450.9
XY.BUPP	483.0	518.9
ET.UOM1	837.0	392.1
NP.9985	382.3	340.4
LD.LD05	461.0	439.1
LD.LD01	507.0	506.3
GS.CVRD	340.0	549.8
ET.UOM2	335.0	354.5
YC.IP02	340.0	316.8
YC.IP05	370.0	457.0
GS.SPFD	464.0	336.3
GS.PTRD	260.0	380.0
YC.IP03	390.0	414.6
YC.IP04	442.0	401.4
AG.WHAR	1190.0	705.1
ET.SWET	840.0	284.7
IU.SSPA	939.0	576.9
NM.CVVA	581.0	244.6
NM.SEAR	984.0	304.8
NM.SIUC	491.0	319.4
NM.UALR	1288	760.0
NQ.NQ793	368.0	356.6
PE.PSUB	551.0	447.9
PN.PPBLN	1077.0	488.5
PN.PPCWF	466.0	310.0
PN.PPMOO	504.0	436.1
PN.PPPCH	429.0	542.7
PN.PPPHS	325.0	244.6
SE.RCRC	519.0	586.7
SE.URVA	528.0	526.9
SE.VWCC	357.0	588.3
US.BLA	700.0	517.3
US.CBN	249.0	206.0
US.GOGA	296.0	709.1
US.LBNH	850.0	760.0
US.LONY	1100	530.2
US.LRAL	568.0	342.6
US.MIAR	1090	311.4
US.MYNC	495.0	760.0
US.NCB	1002	760.0
US.WMOK	1642	558.3
NP.2555	340.0	439.3
US.CBN	279.0	206.0
NP.2511	388.9	285.6
PE.PAGS	525.3	705.2
LD.MVL	671.5	619.6
NP.2648	609.1	571.1
NP.WNC	357.0	612.3
NP.2560	606.8	448.1
XY.JSRW	476.6	263.3
NP.2558	362.0	305.8
XY.URVA	358.9	526.9
GS.LWRD	325.4	263.4
NQ.NQ001	655.4	439.0
NP.2549	497.9	760.0
NP.2405	633.2	321.6
NP.2510	357.5	760.0
US.TZTN	357.5	760.0
NP.2506	431.2	338.9

NP.NAMA	341.5	408.4
NP.CAPTL	334.3	587.9
NQ.NQ957	271.8	285.2
US.CNNC	285.9	598.3
US.MCWV	1483.4	760.0

LIST OF FIGURES

Figure 1. Map of seismic stations used in this study. (a) Map of the Mineral, VA epicentral region showing Modified Mercalli Intensity (MMI) from the 2011 Mw5.8 Mineral, VA earthquake with soil classes for stations determined in this study. The location of the Mineral earthquake (red star) is from McNamara et al., (2014a). The location of the North Anna Nuclear power plant is shown as a white triangle. (b) Map of 218 permanent and portable seismic stations in the EUS at which this study estimated NEHRP soil class (Table 1).

Figure 2**.** Power spectral density (PSD) probability density functions (PDFs) computed for two-components of weak motion (broadband) recordings by portable aftershock station GS.SPFD. Long-term PSDPDF medians (50%) are shown as black dashed lines. Additional percentiles are shown as white (5^{th} percentile) and white dashed lines (90^{th} percentile). The New High and Low Noise Models (grey lines NHNM, NLNM) are from Peterson (1993). (a) PDF formed from 11941 PSDs recorded from August 28, 2011 through March 21, 2012 on channel GS.SPFD.--.BHE. (b) PDF formed from 11939 PSDs from channel GS.SPFD.--.BHZ.

Figure 3. HVSR method using portable aftershock station GS.SPFD and ANSS station US.BLA. (a) Shown are the PSDPDF daily median PSDs for three-components of motion that were used to form daily spectral ratios (red line = BHE, black line = BHN , green line = BHZ). (b) GS.SPFD HVSR results display a clear resonance peak at 3Hz with an amplification factor of 4 (red line) whereas the permanent ANSS rock-site US.BLA has no clear HVSR peak frequency (black line). Dashed lines show the 2σ standard deviation of the daily average HVSR estimate.

Figure 4. Shown are a range of HVSR results for several seismic stations determined in this study. Across the region we observe a range of resonant frequencies and amplification factors. Also shown is the HVSR comparison at IU.DWPF between surface (IU.DWPF.10) and borehole sensor (IU.DWPF.00).

Figure 5. Comparison of co-located weak and strong motion sensors at 3 different seismic stations (Table 1: US.CBN, US.BLA, GS.SPFD). HVSR computed using both weak

motion and strong motion sensors display similar peak frequencies and amplification using co-located sensors.

Figure 6. Comparison of Vs30 (m/s) and HVSR peak frequency (Hz). Black squares show results from 21 permanent and portable seismic stations with surface Vs30 measurements and HVSR resonance frequencies determined in this study. Solid black line shows the least squares fit to the surface HVSR peak frequency and Vs30 with slope (m = 51.90 $\pm$65.95) and intercept (b = 254.73$\pm$28.52) (data standard deviation = 78.91 m/s, data cross correlation coefficient = 0.89). Dashed black lines delineate Vs30 defined NEHRP soil classes (B, C, D).

Figure 7. Comparison between topographic slope and surface measured Vs30 methods seismic stations in the EUS. A least-squares fit results in a slope of 0.173$\pm$0.065 and intercept of 368.79$\pm$42.25 (data standard deviation = 155.79 m/s, data cross correlation coefficient = 0.31) (black line). Also shown are Vs30 estimates based on the HVSR proxy determined in this study (red diamonds). A least-squares fit results in a slope of 0.783$\pm$0.090 and intercept of 99.24$\pm$43.59 (data standard deviation = 69.76 m/s, data cross correlation coefficient = 0.89) (red line).