STATISTICAL COMPARISON OF METHODS FOR ESTIMATING SEDIMENT THICKNESS FROM HORIZONTAL-TO-VERTICAL SPECTRAL RATIO (HVSR) SEISMIC METHODS: AN EXAMPLE FROM TYLERVILLE, CONNECTICUT, USA

Carole D. Johnson, U.S. Geological Survey, Storrs-Mansfield, Connecticut
John W. Lane, Jr., U.S. Geological Survey, Storrs-Mansfield, Connecticut

Abstract

Determining sediment thickness and delineating bedrock topography are important for assessing groundwater availability and characterizing contamination sites. In recent years, the horizontal-to-vertical spectral ratio (HVSR) seismic method has emerged as a non-invasive, cost-effective approach for estimating the thickness of unconsolidated sediments above bedrock. Using a three-component seismometer, this method uses the ratio of the average horizontal- and vertical-component amplitude spectrums to produce a spectral ratio curve with a peak at the fundamental resonance frequency. The HVSR method produces clear and repeatable resonance frequency peaks when there is a sharp contrast (>2:1) in acoustic impedance at the sediment/bedrock boundary. Given the resonant frequency, sediment thickness can be determined either by (1) using an estimate of average local sediment shear-wave velocity or by (2) application of a power-law regression equation developed from resonance frequency observations at sites with a range of known depths to bedrock. Two frequently asked questions about the HVSR method are (1) how accurate are the sediment thickness estimates? and (2) how much do sediment thickness/bedrock depth estimates change when using different published regression equations? This paper compares and contrasts different approaches for generating HVSR depth estimates, through analysis of HVSR data acquired in the vicinity of Tylerville, Connecticut, USA.

Introduction

The horizontal-to-vertical spectral ratio (HVSR) method is a passive seismic technique that uses a single-station three-component seismometer to measure the vertical and horizontal components of ambient seismic noise. Seismic noise in the range of ~0.1 to 1 Hertz (Hz) is induced by ocean waves, large regional storms, and tectonic sources; seismic frequencies greater than 1 Hz generally have a more proximal source including local storms, wind, and anthropogenic activity (Okada and Suto, 2003). The HVSR method utilizes the resonance frequency (f_0) induced in unconsolidated sediments overlying bedrock when there is a substantial contrast in shear-wave acoustic impedance between the two layers (> 2:1). The f_0 is determined from the analysis of the spectral ratio of the horizontal and vertical components of the seismic data. A single HVSR measurement is rapid and non-invasive, making it a cost effective means to estimate sediment thickness.

A comprehensive history of the HVSR method and a passive seismic literature review is provided by Bonnefoy-Claudet et al. (2006). The HVSR method was first introduced by Nakamura (1989) in the context of seismic hazard microzonation studies. Ibs-von Seht and Wohlenberg (1999) and Paroli et al. (2002) applied the HVSR method for sediment thickness mapping in Germany. Both investigations derived site-specific regression equations to estimate the thickness of sediments over bedrock. The HVSR method has been used in the United States in support of groundwater availability and contaminated site investigations (e.g., Lane et al., 2008; Haefner et al., 2011; Bartolino and Adkins, 2012; Fairchild et al., 2013, Bugliosi et al., 2014; Campbell and Landmeyer, 2014). Investigations in the northeastern United States by Lane et al. (2008) and Fairchild et al. (2013) resulted in a site-specific regression equation to determine the thickness of glacial deposits from HVSR measurements near Cape Cod, Massachusetts. Figure 1 shows the regression lines for the German and New England investigations over their range of measured resonance frequencies. In general, the plot shows the equations derived from HVSR measurements in the New England area of the glaciated northeastern United States are similar to one another, but different compared to the equations derived by Ibs-von Seht and Wohlenberg (1999) and Paroli et al. (2002). This comparison suggests that fairly large errors in sediment thickness could be expected if local values for average sediment shear wave velocity, $V_{S,}$ or a local- or regionally-derived regression are not used to analyze resonance frequency data. In this paper, we compare and contrast different approaches for generating HVSR depth estimates through analysis of HVSR data acquired in the vicinity of the Tylerville section, Haddam, Connecticut.

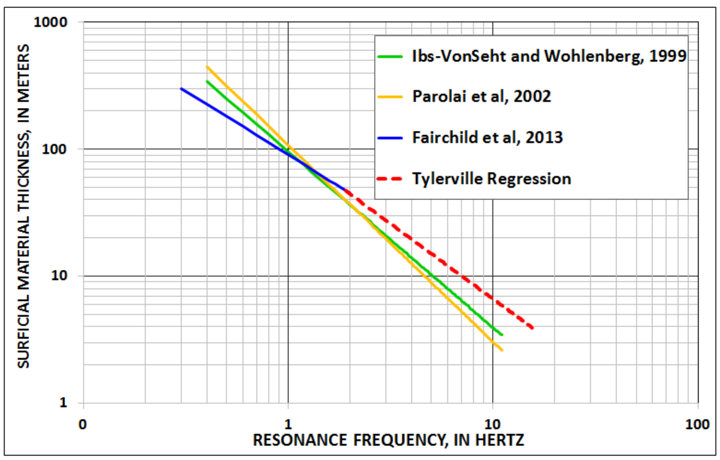

Figure 1. Regression equations relating resonance frequency to thickness of surficial materials.

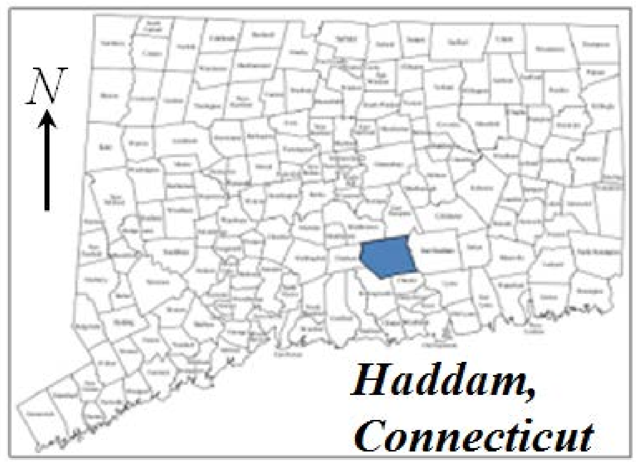

Figure 2. Study area is in the Tylerville section of Haddam, Connecticut.

Data Collection

During summer 2014 and 2015, 176 HVSR measurements were collected by the U.S. Geological Survey (USGS) in the Connecticut River Valley near the Tylerville section of Haddam, Connecticut, in support of a hydrogeologic investigation by the Connecticut Department of Energy and Environmental Protection (CT DEEP) (Figure 2). In the study area, gneissic bedrock is overlain by unconsolidated sediments consisting of alluvium, stratified drift, and ice-contact deposits ranging in thickness from about 1 to 60 m (Stone et al., 2005). The strong acoustic impedance contrast expected at the glacial sediment/metamorphic bedrock boundary provides conditions well-suited for investigation using the HVSR method.

HVSR measurement locations were selected to avoid heavy vehicle and foot traffic, industrial noise, and nearby buildings. For calibration purposes, a total of 24 measurements were made at locations where the depth to rock was known. Most of these measurements produced sharp and interpretable f_0 peaks. A quality code (1-3) for each HVSR plot was assigned based on the visual inspection of the curves. Quality codes of 1 and 2, which respectively indicate good- to moderate-quality spectral plots with easily identifiable peaks were assigned to 156 of the 176 measurements. The remaining HVSR data coded with a 3 were poor quality and were not used to determine sediment thickness.

Four Model TEP-3C Tromino seismometers were used for the HVSR investigation. The general procedure for collecting the HVSR data included the following steps: (1) select a site off of pavement and infrastructure, and clear of soft debris as needed; (2) orient seismometer to magnetic north and firmly couple with the earth by pressing the spikes on the bottom of the unit into the ground; (3) level the seismometer using the spirit level on the top of the unit; and (4) record data for about 20 minutes per site. Recording times were increased near high-traffic or noisy areas, and measurements were repeated whenever poor unit coupling was observed.

Data Processing and Interpretation

A commercially available program (Grilla V6.1) and a freeware processing suite (Geopsy V2.7.0) were used to process the passive seismic data and determine f_0. Data processing included the use of band-pass filtering to remove instrument drift, data spikes, and other high-frequency noise, and a post-processing spectral smoothing method described by Konno and Ohmachi (1998). Both programs compute the average spectrums of the two horizontal components and the vertical component for a user-specified time-window (Figure 3a) and then calculate the ratio of the horizontal and vertical amplitude spectrums. The plotted spectrums were examined to determine resonance peak and f_0 (Figure 3b).

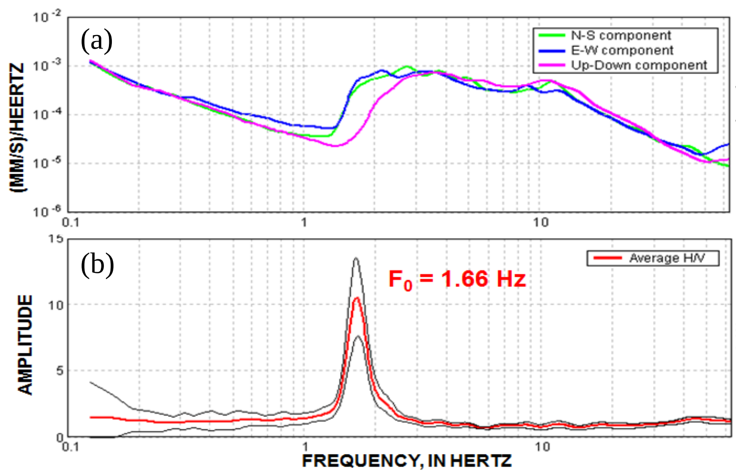

Figure 3. (a) Example of three three-component ambient noise and (b) spectral plot of the ratio of the averaged horizontal-to-vertical components (red) ±1 standard deviation (gray), showing the fundamental frequency, f_0.

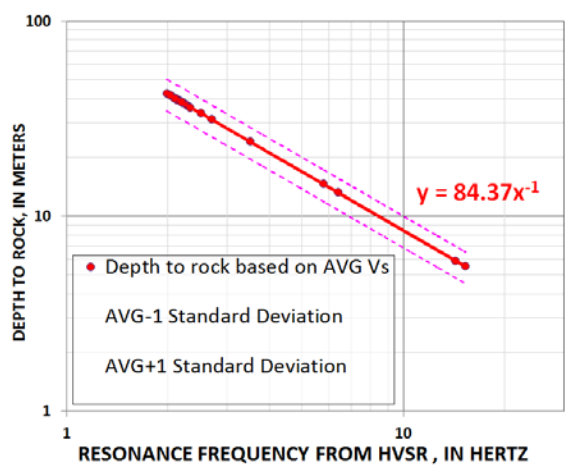

Figure 4. Depth to rock based on average shear wave velocity (337.5 m/s, red) ±1 standard deviation (62.3 m/s, pink dashed) for Tylerville, Connecticut, calibration points.

Development of local equations

Two approaches were used to estimate the depth to bedrock using the f_0 obtained from the HVSR measurements. The first approach used a uniform estimate of V_S, and the second used a local regression equation to compute sediment thickness. In the first approach, the average V_S was computed at locations with known depth to rock using $V_S = \sum_{i=1}^{n}(4Z_i f_{0i})/n$, where n is the number of locations where the depth to rock is known (meters per second (m/s)); Z is the thickness of the unconsolidated sediments (m) at location i, and f_{oi} is the resonance frequency (Hz) determined from HVSR measurements at site *i*. At sites where sediment thickness was unknown, thickness was computed using: $Z = V_S/4f_0$. The average V_S for the 24 calibration sites of the Tylerville dataset was estimated to be 337.5 m/s with a standard deviation of 62.7 m/s. This average V_S is consistent with borehole V_S measurements from overburden wells in Haddam Meadows State Park (HMSP), 5 miles north of Tylerville. At HMSP, borehole V_S is 125 to 362 m/s with an average of 299 m/s (written commun., Shelby Peterie, Kansas Geological Survey, 2009). Advantages of the average *Vs* HVSR analysis method include computational simplicity and the ease of applying standard deviation confidence intervals (Figure 4).

The second HVSR analysis approach used a Tylerville-specific regression equation to solve for sediment thickness. For the calibration sites with a known depth to rock, a power law function was fit to the HVSR-determined f_0 versus depth to rock. The overburden thickness is computed as: $Z = C\ f_0\ ^a$ where C is a constant (in meters for this investigation), and the exponent a controls the slope of the regression line (straight line on a log-log plot). If a = -1, then V_S is uniform with depth. For Tylerville, the local regression equation was $Z = 100.95\ f_0\ ^{-1.18}$ with a coefficient of determination (R^2) of 0.93 (dashed red line in Figure 1).

How statistically different are these results?

A dummy variable regression (DVR) test was conducted to assess the statistical difference between the Tylerville regression (Z=100.95$f_0^{-1.184}$) and Tylerville average *Vs* equation ($Z=337.7/4f_0$) (Helsel and Hirsch, 2002). In addition, the Tylerville regression was statistically compared to the regression equation for Cape Cod (Fairchild et al., 2013), and to the regression for Cologne, Germany (Ibs-von Seht and Wohlenberg, 1999), which HVSR practitioners sometimes use *in lieu* of local or regional calibration equations.

For the DVR analysis, the data were transformed to log f_0 and log sediment thickness. A dummy code or categorical variable was set to 0 (for the reference) and 1 (for the test dataset), and the dummy variables were used in the regression and analysis of variance. The DVR procedure tests the null hypothesis (H_0) that the regression coefficient (slope of the line) for the reference set is the same as the regression coefficient for another site or equation. The 'R' statistical package (R Core Team, 2015) was used to perform the DVR and to provide a test statistic *t* and a *p*-value (Helsel and Hirsch,2002). If the *p*-value is less than the confidence level (alpha), then the H_0 is rejected. The DVR tests showed that the Tylerville regression was statistically different at a 99% confidence level from the Ibs-von Seht and Wohlenberg and the Cape Cod regressions, but only weakly different from the Tylerville average V_S equation (Table 1).

Table 1. Components of the regressions and the statistical significance of the dummy variable regression tests.

Site	Average Vs (m/s)	Standard Deviation	Regression, C	Regression, a	t	Pr >| t|
[1]TY regression			100.95	-1.184	--	reference
TY average V_s	337.65	62.7	84.4	-1	2.474	0.017*
Cape Cod (Fairchild et al., 2013)	362.1		90.52	-1	3.252	0.002**
Ibs-von Seht and Wohlenberg (1999)	--	--	96.6	-1.388	-3.908	0.000262***

[1] TY indicates Tylerville, *at a significance of alpha = 0.05 (95% confidence), **at a significance of alpha = 0.01 (99% confidence), ***at a significance of alpha = 0.001 (99.9% confidence).

The results of the DVR statistical testing underscore the value of using local calibration information to develop local regression equations whenever possible. In the absence of sufficient data points for a meaningful local regression equation or in the case of a limited range in the depths of available calibration points, computation of a local average V_S from a few high quality HVSR measurements at locations of known sediment thickness should be considered before using a regression equation from a distant locality.

Determination of the bedrock surface

Data from the HVSR method were used to map the topographic surface of the bedrock for the Tylerville area (Figure 5a). The sediment thickness below land-surface elevation was interpolated in Oasis Montaj (v8.5.2) using the minimum curvature algorithm. In addition to the HVSR data points, 'zero-depth' control points were added at bedrock outcrop locations.

In the Tylerville study area, the bedrock surface compiled from the HVSR measurements slopes from west to east toward the Connecticut River. In addition, there are several minor variations on the bedrock surface suggestive of buried channels or small-scale glacial erosion features. Sediment thickness estimates along profile A-A' for the four different HVSR analysis approaches are shown in Figure 5b. The sediment thicknesses estimated with the Tylerville regression and the average V_S method differ by a root mean square error (RMSE) of 3.7 m over the profile. For the Tylerville and Cape Cod regressions, the estimated thicknesses have a RMSE of 1.5 m. The Tylerville and Ibs-von Seht and Wohlenberg (1999) regression results differ by a RMSE of 7.3 m. However, most regression equation estimates fall within the envelope of the average Vs +/- 1 standard deviation (shaded zone in Figure 5b).

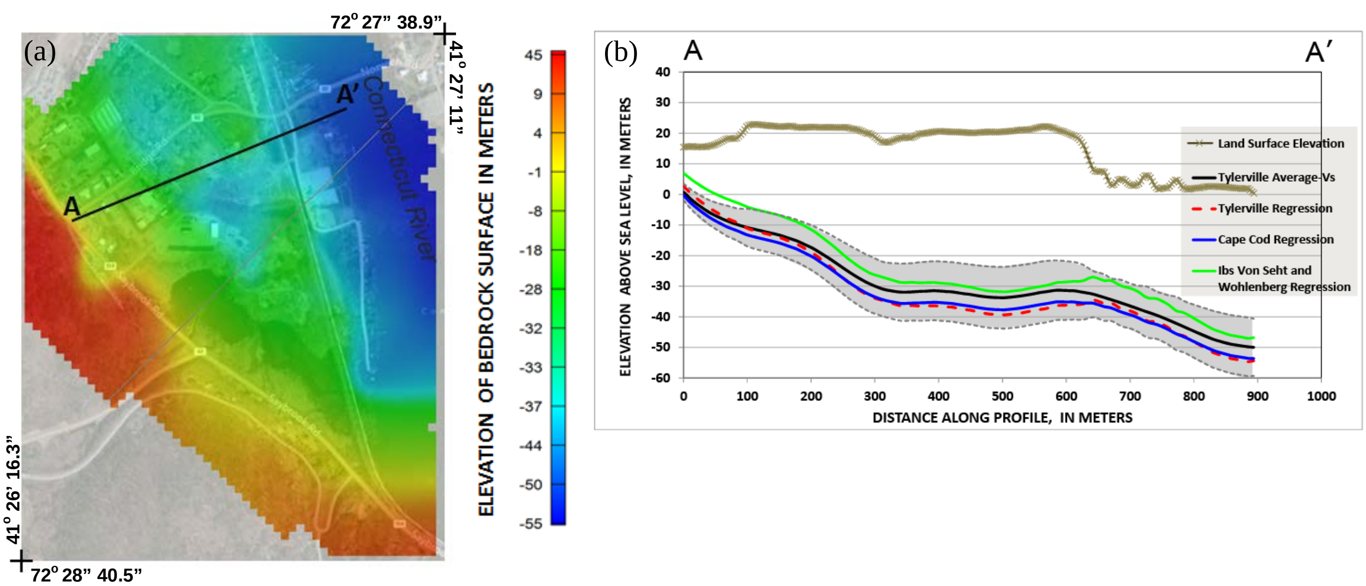

Figure 5. (a) Topography of the bedrock surface estimated using the average *Vs* from HVSR measurements for Tylerville, Connecticut. Elevation in meters is represented by color. (b) Cross-section A-A' from southwest to northeast shows the elevation of the bedrock surface estimated for the Tylerville regression equation (dashed red) and the average *Vs* (black), and is compared to results using the regressions of Ibs-von Seht and Wohlenberg (1999; green) and Fairchild et al. (2013; blue). The shaded region shows bedrock surface elevation generated using the average Tylerville *Vs* ±1 standard deviation.

Conclusions

HVSR is an increasingly popular and cost-effective method for determining the thickness of unconsolidated sediments and delineating bedrock topography. During 2014 and 2015, the USGS collected 176 HVSR measurements in the Tylerville, Connecticut, area. The HVSR measurements were processed and analyzed to determine f_0. A total of 156 HVSR measurements exhibited well-defined f_0 peaks suitable for sediment thickness analysis. Sediment thicknesses computed using average V_S statistics, a least-squares regression equation, and two other published regressions were compared using DVR analysis to determine statistical differences between the methodologies. The DVR results showed that the statistical difference between the Tylerville regression equation and the Tylerville average V_S method was small, but significant at the 95% confidence level. However, the Tylerville regression equation was statistically different from published regressions from Cape Cod, Massachusetts, and Cologne, Germany at the 99% confidence level.

Although use of published regression equations may provide useful initial estimates of sediment thickness trends, our analysis shows that fairly large errors in the computed sediment thickness (up to 8 m at Tylerville using the local regression compared to the regression equation from Cologne, Germany) could occur if an inappropriate regression equation is used. Further efforts are needed to evaluate regression equations from different sites in order to assess and describe factors controlling resonance frequency. A “library” of regression equations developed for specific regions and (or) type geologic settings could improve sediment thickness estimated by HVSR practitioners. However, if sufficient f_0 measurements at calibration points spanning a range of depths are available, development of a local regression or use of local average Vs along with the range of uncertainty to interpret HVSR f_0 is preferred.

Acknowledgments

We appreciate the contributions of Eric White, Tiffany Taylor, and Brianna Church of the USGS and acknowledge the support of Shannon Pociu of the CT DEEP. The authors also thank the land owners in Tylerville, Connecticut, for providing access to their land for HVSR measurements. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Bartolino, J.R., and Adkins, C.B., 2012, Hydrogeologic framework of the Wood River Valley aquifer system, south‑central Idaho: U.S. Geological Survey Scientific Investigations Report 2012–5053, 46 p., 1 plate in pocket. Available online at URL: http://pubs.usgs.gov/sir/2012/5053/

Bonnefoy-Claudet S, Cotton, F., and Bard P.Y., 2006, The nature of seismic noise wavefield and its implications for site effects studies—A literature review: Earth-Science Reviews, 23 p.

Bugliosi, E.F., Miller, T.S., and Reynolds, R.J., 2014, Hydrogeology and water quality of the stratified-drift aquifer in the Pony Hollow Creek Valley, Tompkins County, New York: U.S. Geological Survey Scientific Investigations Report 2014-5059, 23 p.

Campbell, B.G., and Landmeyer, J.E., 2014, Groundwater availability in the Crouch Branch and McQueen Branch aquifers, Chesterfield County, South Carolina, 1900–2012: U.S. Geological Survey Scientific Investigations Report 2014–5050, 68 p., http://dx.doi.org/10.3133/sir2014505

Fairchild, G.M., Lane, J.W., Jr., Voytek, E.B., and LeBlanc, D.R., 2013, Bedrock topography of western Cape Cod, Massachusetts, based on bedrock altitudes from geologic borings and analysis of ambient seismic noise by the horizontal-to-vertical spectral-ratio method: U.S. Geological Survey Scientific Investigations Map 3233, 1 sheet, maps variously scaled, 17-p. pamphlet, on one CD–ROM.

Haefner, R.J., Sheets, R.A., and Andrews, R.E., 2011, Evaluation of the horizontal-to-vertical spectral ratio (HVSR) seismic method to determine sediment thickness in the vicinity of the South Well Field, Franklin County, Ohio: Ohio Journal of Science, v. 110, no. 4, p. 77–85.

Helsel, D.R. and R. M. Hirsch, 2002. Statistical Methods in Water Resources Techniques of Water Resources Investigations, Book 4, chapter A3. U.S. Geological Survey. 522 pages.

Ibs-von Seht, M., and Wohlenberg, J., 1999, Microtremors measurements used to map thickness of soft soil sediments: Bulletin of the Seismological Society of America, v. 89, p. 250-259.

Konno, K., and Ohmachi, T., 1998, Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor: Bulletin of the Seismological Society of America, v. 88, p. 228-241.

Lane, J.W., Jr., White, E.A., Steele, G.V., and Cannia, J.C., 2008, Estimation of bedrock depth using the horizontal-to-vertical (H/V) ambient-noise seismic method, *in* Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 6-10, 2008, Philadelphia, Pennsylvania, Proceedings: Denver, Colorado, Environmental and Engineering Geophysical Society, 13 p.

Nakamura, Y., 1989, A method for dynamic characteristics estimations of subsurface using microtremors on the ground surface: Quarterly Report RTRI, Japan, v. 30, p.25-33.

Okada, H., and Suto, K., 2003, The Microtremor Survey Method, Geophysical Monograph Series Number 12: Tulsa, Oklahoma, Society of Exploration Geophysicists, 135 p.

Parolai, S., Bormann, P., and Milkert, C., 2002, New relationships between *Vs*, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for Cologne Area (Germany): Bulletin of the Seismological Society of America, v. 92, p. 2521-2527.

R Core Team, 2015, R—A language and environment for statistical computing: R Foundation for Statistical Computing, Vienna, Austria, https://www.R-project.org/

Stone, J.R., Schafer, J.P., London, E.H., DiGiacomo-Cohen, M .L., Lewis, R.S., and Thompson, W.B., 2005, Quaternary Geologic Map of Connecticut and Long Island Sound Basin: Scientific Investigations MapSIM-2784, U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia, USA.

Final copy as submitted to Environmental and Engineering Geophysical Society for publication as: Johnson, C.D. and Lane, J.W., Jr., 2016, Statistical comparison of methods for estimating sediment thickness from horizontal-to-vertical spectral ratio (HVSR) seismic methods: An example from Tylerville, Connecticut, USA, *in* Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 20-24, 2016, Denver, Colorado, Proceedings: Denver, Colorado, Environmental and Engineering Geophysical Society, 7 p.