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, OH

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Abstract. The horizontal-to-vertical spectral ratio (HVSR) seismic method involves analyzing measurements of ambient seismic noise in three dimensions to determine the fundamental site resonance frequency. Resonance is excited by the interaction of surface waves (Rayleigh and Love) and body waves (vertically incident shear) with the high-contrast acoustic impedance boundary at the bedrock-sediment interface. Measurements were made to determine the method's utility for estimating thickness of unconsolidated glacial sediments at 18 locations at the South Well Field, Franklin County, OH, and at six locations in Pickaway County where sediment thickness was already known. Measurements also were made near a high-capacity production well (with pumping on and off) and near a highway and a limestone quarry to examine changes in resonance frequencies over a 20-hour period. Although the regression relation for resonance frequency and sediment thickness had a relatively low r^2 (0.322), estimates of sediment thickness were, on average, within 14 percent of known thicknesses. Resonance frequencies for pumping on and pumping off were identical, although the amplitude of the peak was nearly double under pumping conditions. Resonance frequency for the 20-hour period did not change, but the amplitude of the peak changed considerably, with a maximum amplitude in the early afternoon and minimum in the very early morning hours. Clay layers within unconsolidated sediments may influence resonance frequency and the resulting regression equation, resulting in underestimation of sediment thickness; however, despite this and other complicating factors, hydrogeologists should consider this method when thickness data are needed for unconsolidated sediments.

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INTRODUCTION

The City of Columbus South Well Field (SWF) is approximately eight kilometers south of the city and provides an average of 20 million gallons of water per day to the citizens and industries of Columbus. The SWF includes four high-capacity production wells completed in a glacially derived sand and gravel aquifer adjacent to the Scioto River and Big Walnut Creek (Fig. 1A). The sand and gravel aquifer is about 15 to 35 meters thick in this area and, locally, may include clay layers that lie on top of bedrock or interfinger with the sand and gravel (Schmidt and Goldthwait 1958). Underlying bedrock is composed of Devonian and Silurian limestone, dolomite, and shale. Sand, gravel, and limestone quarrying operations surround the SWF on the north, east, and south sides.

The thickness of the sand and gravel and corresponding depth to bedrock is important for understanding the sources of water to the production wells and potential effects of quarrying on groundwater resources of the area. The mining company is dewatering the sand and gravel mining pits and mining the underlying limestone adjacent to the well field. Throughout the SWF area, borings and wells completed into bedrock have been used by other workers to develop contour maps of the bedrock surface (Sedam and others 1989; Brockman and others 2003). However, large parts of the area have no depth-to-bedrock data from borings or wells, and the contour maps in those areas are interpolated estimations of the bedrock-surface elevation.

Passive-seismic site characterization by means of the horizontal-to-vertical spectral ratio (HVSR) method (also known as the Nakamura method (Nakamura 1989)) has been successfully used to determine the thickness of unconsolidated sediments in sedimentary basins throughout the world (Ibs-von Seht and Wohlenberg 1999; Parolai and others 2002; Picozzi and others 2008). The HVSR method is a passive seismic method because the measurements do not require a user-generated seismic energy source. Instead, the method relies on measurement of ambient noise caused by wind, ocean waves, and human activity. The seismic noise is recorded with a single broadband three-component seismometer and processed after collection to determine the resonance frequency. The resonance frequency is determined by calculating the spectral ratio of horizontal over vertical (H/V) ground motion in the seismic record. Resonance frequency has been shown to be proportional to the thickness of unconsolidated sediments (Nakamura 1989; Bonnefoy-Claudet and others 2006a; van der Baan 2009).

Researchers are divided over the theoretical basis of using HVSR to determine sediment thickness (van der Baan, 2009). However, several studies, including some numerical modeling studies, indicate that surface waves (Raleigh or Love) may amplify H/V characteristics at a particular site (Bonnefoy-Claudet and others 2006b; van der Baan 2009). Vertically incident, horizontally polarized shear waves (SH-waves) also may contribute strongly to the H/V spectral ratio. Ibs-von Seht and Wohlenberg (1999) showed that a transfer function can be used to describe the resonance frequency (f_r) of a simple two-layer system of soft sediment (with a shear-wave velocity, Vs, and thickness, Z) covering a hardrock basement:

$$f_r = (n^*Vs/4)\ Z^{-1} \qquad (1)$$

where n = 1, 3, 5, etc. The fundamental resonance frequency (f_{r0}) is given when n = 1 and higher order modes of the resonance frequency are given by n greater than one. Resonance frequencies occur for thicknesses that are uneven multiples of the wavelength (λ) divided by four. Regardless of the theoretical basis, the HVSR method is based on the assumption of a large contrast in acoustic impedance, which is proportional to material density multiplied

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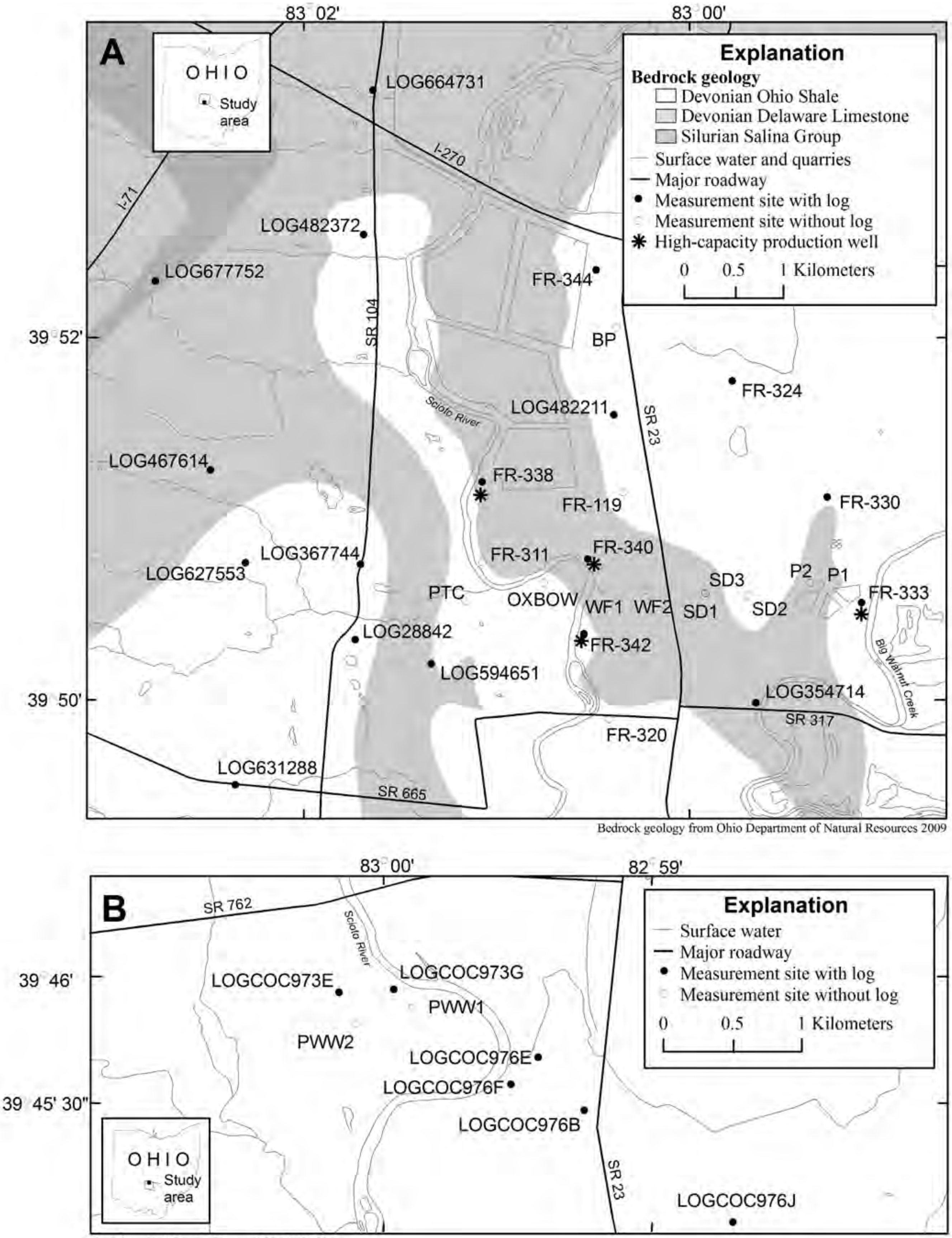

Bedrock geology from Ohio Department of Natural Resources 2009

Base from U.S. Census Bureau 2000, 1:100,000
Lambert Conformal Conic projection
Standard parallels 38 44'N and 40 02'N
Central meridian 82 30'W

FIGURE 1. Measurement sites in (A) the South Well Field area, Franklin County, OH, and (B) the study area in Pickaway County, OH. Entire Pickaway County study area is underlain by Devonian Ohio Shale.

by shear-wave velocity, between the unconsolidated sediments and bedrock.

This paper details the results of multiple experiments using the HVSR method in the SWF area. The purpose of this study is, at least in part, to determine whether the HVSR method can be used to determine unconsolidated sediment thickness given well locations with known depth to bedrock and measured H/V spectral ratios. A secondary purpose of this work was to evaluate the accuracy of the method in the geologic setting surrounding the SWF. Comparisons of the results of the method with known sediment thickness and with other similar studies are provided.

MATERIALS AND METHODS

The HVSR method was used throughout the SWF in August 2009 to determine whether the method could provide reasonable estimates of sediment thickness. Instrumentation included the Güralp® 3-component seismometer hard-wired to a field laptop computer. (Use of trade or product names is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey (USGS) or the City of Columbus.) The seismometer was placed on a steel plate coupled to soils free of loose vegetation and was protected from wind noise by an inverted bucket. Scream! software (Güralp Systems 2009) was used to collect the passive seismic data in the field. Typically, six sets of five-minute data (for a total of 30 minutes at each site) were collected. Proximity to potential sources of extraneous noise (including roads, power lines, water-transmission pipelines, and trees) and wind speed were recorded at each site. A real-time global positioning system (GPS) was used to collect accurate time information. A hand-held GPS was used for latitude and longitude determination. Land-surface elevation at each measurement location was determined from digital LiDAR data collected in 2006 (Ohio State Wide Imagery Program 2010).

Four different sets of experiments were done at sites throughout the SWF area:

1. Eighteen seismic-noise measurements were made at locations throughout the SWF area (Fig. 1A) to determine the relation between H/V resonance frequency and sediment thickness. These measurements were made at locations where sediment thickness and stratigraphy from well logs were available. The measurement sites included four sites adjacent to high-capacity production wells. For the purposes of this experiment, the nearby well was turned off at each of these sites while performing seismic-data collection. Thirteen additional measurements were made at locations where no previous data were available.
2. Eight seismic-noise measurements were made at a proposed well field in Pickaway County (approximately 10 kilometers to the south of the SWF) to determine the transferability of the results at another site with similar sediment and bedrock characteristics (Fig. 1B). Six of these measurements were made at locations where well logs were available; two measurements were made at locations where no previous data were available.
3. Two seismic-noise measurements were made at a single site to evaluate the effect of pumping at a nearby high-capacity production well on the calculated resonance frequencies. The first measurement was taken while the high-capacity production well was pumping at about six million gallons per day; the second-was made at the same location while the pump was off. Only the "pump off" results were included in Experiment 1, above.
4. Continuous seismic-noise measurements were obtained at a single site over a 20-hour period to examine changes in frequencies and (or) amplitudes that may be related to changes in traffic and industrial noise throughout the course of a typical weekday.

Post-processing and analysis of all seismic data were done with Geopsy software v.2.6.3 (Geopsy Project 2009). H/V frequencies and amplitudes were filtered by using an "anti-triggering" function in the software for each site that subdivided the records into at least 60-second time windows that were free of transient noise (wind, footsteps, passing vehicles, etc.). Records from the two horizontal components were combined by using a squared average. A smoothing function (Konno and Ohmachi 1998) with a smoothing constant of 40 and five-percent cosine taper was used to smooth the horizontal and vertical spectra. The H/V amplitudes were plotted against the frequencies of the signal between zero and 10 hertz to determine a peak resonance frequency. A typical plot of H/V amplitudes versus frequency is shown in Fig. 2 (on subsequent figures, only the average values, which are shown as a solid black line in Fig. 2, are shown). The peak resonance frequencies were then graphically correlated to sediment thickness through a power function:

$$Z = af_{r0}^{\ b} \tag{2}$$

where Z = sediment thickness; f_{r0} = seismic resonance frequency, in hertz; a,b = empirically determined fitting parameters from non-linear regression of f_{r0} data at sites where Z is known; a is a function of the shear-wave velocity (see Equation 1 above); and b is the depth dependence of the shear-wave velocity (Ibs-von Secht and Wahlenberg 1999). In Equation 1 above, if $n = 1$ (the first uneven multiple of $\lambda/4$), then $a = Vs/4$, and $b = -1$, which indicates that shear-wave velocities increase with depth.

RESULTS

Experiments 1 and 2

H/V measurements were made at 18 sites (Fig. 1 and Table 1) near the SWF where sediment thickness was known from borings or well-log data. Figure 3 shows the data plotted along with regression lines from this and previous HVSR method studies (Ibs-von Seht and Wolenberg 1999; Parolai and others 2004; and USGS unpublished data from measurements made in glacial sediments on Cape Cod, Massachusetts (available upon request from lead author)). This approach assumes that a uniform shear-wave velocity is present throughout the unconsolidated sediments in the study area. The data collected during this study did not correlate well with the regression lines generated from previous studies (Fig. 3). All data points collected during this study where sediment thickness was known indicated that, for a particular resonance frequency, a greater sediment thickness is observed than

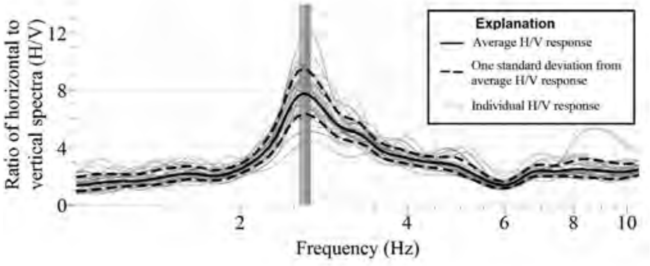

FIGURE 2. Typical graphical output from Geopsy software of the ratio of horizontal to vertical spectra (H/V) as a function of frequency. For this example from site FR-330, the peak amplitude between one and 10 hertz is associated with a resonance frequency of 2.59 hertz.

Table 1

Site Characteristics and Estimated Sediment Thickness for Horizontal to Vertical Spectral Ratio Measurements at Franklin and Pickaway Counties, Ohio. [ODNR, Ohio Department of Natural Resources; COC, City of Columbus; NAD 83, North American Datum of 1983; H/V, horizontal over vertical seismic; --, not available]

Site	ODNR or COC well log number	Land surface elevation (meters above mean sea level)	Latitude (decimal degrees referendced to NAD 83)	Longitude (decimal degrees referenced to NAD 83)	Calculated resonance frequency (hertz)	Uncosolidated sediment thickness from well log (meters)	Unconsolidated sediment thickness from H/V regression equation (meters)	Difference	
								(meters)	(percent)
South Franklin County Well Field sites with well logs									
FR-324	COC FR-324	217.62	39.86261	82.99534	3.56	36.3	33.3	3.0	8
FR-330	COC FR-330	223.88	39.85209	82.98674	2.59	59.1	40.8	18.3	31
FR-333	COC FR-333	220.64	39.84251	82.98362	3.16	51.5	36.0	15.5	30
FR-338	COC FR-338	209.16	39.85346	83.01801	3.86	25.6	31.7	-6.1	-24
FR-340	COC FR-340	212.44	39.84646	83.00842	3.71	36.3	32.5	3.8	10
FR-342	COC FR-342	208.48	39.83968	83.00877	3.71	31.7	32.5	-0.8	-3
FR-344	COC FR-344	215.69	39.87267	83.00768	3.71	32.9	32.5	0.4	1
LOG28842	ODNR 28842	219.08	39.83916	83.02950	3.04	31.7	36.9	-5.2	-16
LOG354714	ODNR 354714	214.82	39.83348	82.99321	2.69	36.3	39.8	-3.5	-10
LOG367744	ODNR 367744	220.78	39.84598	83.02902	2.94	27.4	37.7	-10.3	-37
LOG467614	ODNR 467614	227.45	39.85452	83.04261	4.39	37.2	29.2	8.0	21
LOG482211	ODNR 482211	226.59	39.85954	83.00607	2.80	33.2	38.8	-5.6	-17
LOG482372	ODNR 482372	219.85	39.87587	83.02872	4.70	28.0	28.0	0.0	0
LOG594651	ODNR 594651	217.91	39.83698	83.02260	3.36	36.3	34.6	1.7	5
LOG627553	ODNR 627553	223.19	39.84612	83.03945	4.04	29.0	30.8	-1.8	-6
LOG631288	ODNR 631288	222.93	39.82603	83.04036	4.53	30.5	28.7	1.8	6
LOG664731	ODNR 664731	214.99	39.88896	83.02789	5.11	22.9	26.6	-3.7	-16
LOG677752	ODNR 677752	231.36	39.87166	83.04758	2.8	34.7	38.8	-4.1	-12
						Mean absolute difference		5.2	14
South Franklin County Well Field sites without well logs									
PTC	--	215.27	39.84265	83.01952	3.42	--	34.2	--	--
BP	--	221.15	39.86750	83.00580	3.16	--	36.0	--	--
FR-119	--	226.48	39.85254	83.00522	2.49	--	41.8	--	--
FR-311	--	209.02	39.84619	83.01797	4.02	--	30.9	--	--
FR-320	--	213.49	39.83200	83.00650	3.49	--	33.8	--	--
OXBOW	--	208.74	39.84430	83.01240	3.07	--	36.7	--	--
P1	--	221.99	39.84419	82.98736	9.02	--	18.6	--	--
P2	--	220.23	39.84430	82.98829	2.59	--	40.8	--	--

Table 1 (cont.)

Site Characteristics and Estimated Sediment Thickness for Horizontal to Vertical Spectral Ratio Measurements at Franklin and Pickaway Counties, Ohio. [ODNR, Ohio Department of Natural Resources; COC, City of Columbus; NAD 83, North American Datum of 1983; H/V, horizontal over vertical seismic; --, not available]

Site	ODNR or COC well log number	Land surface elevation (meters above mean sea level)	Latitude (decimal degrees referendced to NAD 83)	Longitude (decimal degrees referenced to NAD 83)	Calculated resonance frequency (hertz)	Uncosolidated sediment thickness from well log (meters)	Unconsolidated sediment thickness from H/V regression equation (meters)	Difference	
								(meters)	(percent)
SD1	--	222.67	39.84336	82.99775	6.49	--	22.9	--	--
SD2	--	221.10	39.84320	82.99400	2.71	--	39.6	--	--
SD3	--	222.21	39.84340	82.99778	2.59	--	40.8	--	--
WF1	--	212.89	39.84377	83.00713	4.05	--	30.8	--	--
WF2	--	213.39	39.84360	83.00330	3.32	--	34.9	--	--
Pickaway County sites with well logs									
LOGCOC973E	COC 973E	209.93	39.76625	83.00749	4.22	31.7	30.0	1.7	5
LOGCOC973G	COC 973G	205.98	39.76644	83.00394	3.91	22.9	32.0	-9.1	40
LOGCOC976B	COC 976B	211.49	39.75857	82.99156	2.89	42.7	38.1	4.6	11
LOGCOC976E	COC 976E	212.10	39.76202	82.99455	3.07	37.8	36.7	1.1	3
LOGCOC976F	COC 976F	212.33	39.76026	82.99632	2.98	39.6	37.4	2.2	6
LOGCOC976J	COC 976J	209.53	39.75129	82.98190	2.55	66.4	41.2	25.2	38
						Mean absolute difference		7.4	17
Pickaway County sites without well logs									
PWW1	--	205.81	39.762523	83.00273	3.37	--	34.6	--	--
PWW2	--	205.03	39.76422	83.00641	4.18	--	30.2	--	--

expected relative to published regression equations. This consistent underestimation indicated that a site-specific regression equation was needed. The equation and resulting coefficient of determination ($r^2 = 0.322$) for the SWF data are shown on the figure.

The mean absolute difference between sediment thickness from well logs in the SWF area and those estimated by the HVSR method was 5.2 m (about 14 percent). If the relations observed in SWF area are extended to measurements obtained in Pickaway County, the mean absolute difference for Pickaway County sites is 7.4 m (17 percent).

Experiment 3

Measurements were made at site FR-340 while a high-capacity production well was pumping at about six million gallons per day and again when it was not pumping. Figure 4 shows the average resonance frequency for both measurements. The peak resonance frequency for both the pumping measurement and non-pumping measurement was 3.71 hertz, which corresponds to a depth of about 33 m from the regression equation. The measured sediment thickness from the well log is 36 m. No change in resonance frequency or calculated sediment thickness was determined for pumping as compared to non-pumping conditions. However, the amplitude of the resonance frequency while the production well was pumping was more than two times the amplitude when the pump was off, indicating that the horizontal ground motion increased relative to vertical motion in the sediments because of additional noise contributed by the pump and, perhaps, because of groundwater flowing to the well and (or) the discharging water being conveyed through a large-diameter pipe.

Experiment 4

A 20-hour set of continuous measurements was recorded at site LOG664731 on 19-20 Aug. 2009 on the north side of the study area. This site is between a golf course to the west and an active limestone quarry to the east. State Route 104 runs north-south between the golf course and quarry and includes traffic from automobiles and heavy trucks. Estimated mid-day traffic when field crews were on site was 80 to 100 cars plus 15 large trucks per hour. Many of the trucks carried full loads of limestone out of the nearby quarry. The seismometer was placed approximately 35 meters west of the road.

Figure 5 shows the average resonance frequency in relation to H/V for 30-minute periods over the 20-hour period. Although the shape of the curves changes slightly over the 20-hour period and the amplitude of the peak varies, the value of the peak resonance frequency does not change with time. As shown in Fig. 6, the amplitudes of the peak resonance frequencies were greatest from about noon to 5 p.m. and were lowest at about 4 a.m., which likely corresponds to the amount of traffic moving along State Route 104. Records of quarry activity were unavailable. The resonance frequency of 5.11 hertz corresponds to a sediment thickness of 27 m from the regression equation. The measured sediment thickness from the well log was 23 m.

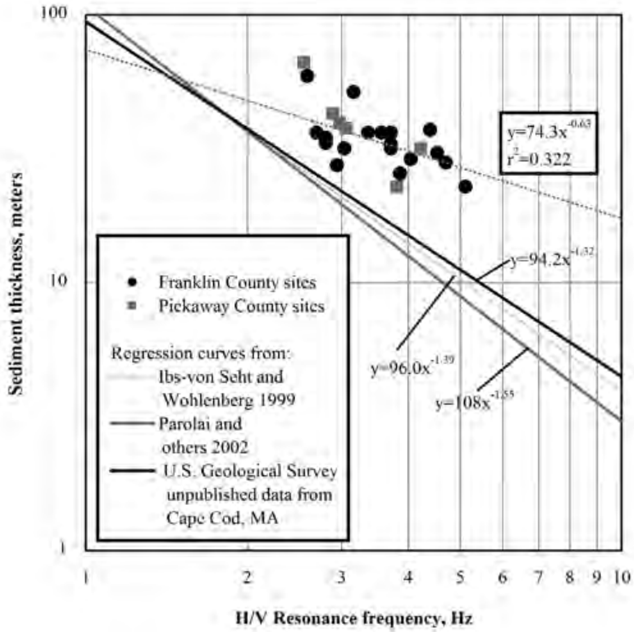

FIGURE 3. Ratio of horizontal-to-vertical spectra (H/V) resonance frequency as a function of sediment thickness at sites in Franklin and Pickaway counties, OH. Regression curves from other studies are included for reference.

DISCUSSION

As noted above, the HVSR method provided results that were, on average, within 14 percent of sediment thicknesses obtained from well logs. For many hydrogeologic studies, this level of accuracy may be adequate, especially in areas where data are limited or unavailable. Sources of error may include those introduced in data acquisition and processing, the presence of clay layers within the unconsolidated section, and varying types of bedrock which can complicate interpretation of the resonance frequencies. Data acquisition and processing errors were minimized by following procedures to minimize activities at the site and record possible interference with the signal. It is likely that the largest errors in sediment thickness arise from variability of geology (shear-wave velocity) in the subsurface.

At the SWF, further exploration of the effects of clay layers and the types of bedrock could be useful because the HVSR method relies on a high acoustic impedance contrast between unconsolidated sediments and bedrock to produce the best results. Clay layers are commonly found within the glacial sediments and (or) on top of bedrock throughout the well field area, and in some well logs, the thickness of the clay exceeds five meters. As observed by Ibs-von Seht and Wohlenberg (1999), deviations from the strict linear relations between resonance frequency and sediment thickness could be attributed to heterogeneities within the unconsolidated sediments. Figure 7 shows well logs with more than five meters of clay overlying bedrock. For 10 of the 12 sites where clay is greater than five meters thick, the data points lie above the regression line obtained for the Franklin County sites. This pattern indicates that the resonance frequency is higher than expected given thickness of sediments provided by the well logs and that the frequency might actually be indicative of the depth to the top of the clay layer instead. It is important to note, however, the presence of the clay would not necessarily be known beforehand in a hydrogeological study where well-log data are sparse.

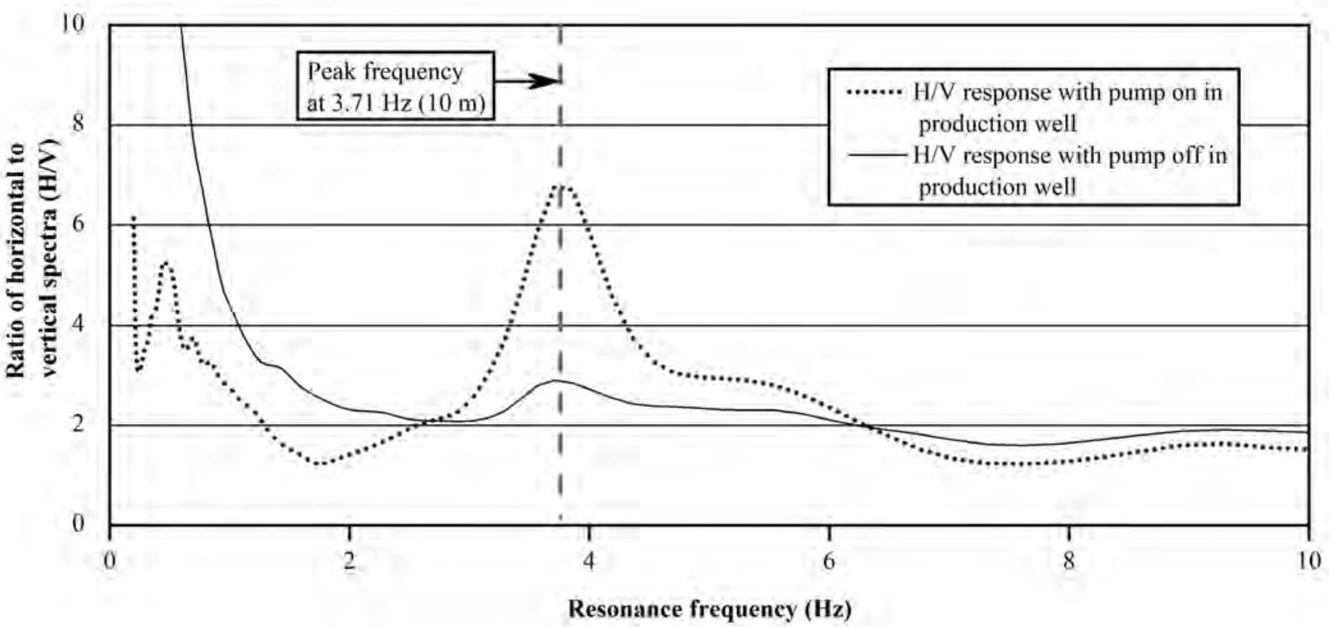

FIGURE 4. Ratio of horizontal to vertical spectra (H/V) as a function of resonance frequency for two measurements made at site FR-340 while pumping at a high-capacity production well was on and off.

In addition to clay layers (which are present in some places and absent in others), three different bedrock units lie beneath the SWF study area: the Ohio Shale and the Columbus Limestone of Devonian age and the Salina Group of Silurian age, the Salina being predominantly dolomite under the well field area (Fig. 1A). For the Pickaway County study area, the entire area is underlain by the Ohio Shale (Fig. 1B). Data points in Fig. 7 discriminate formations under each particular measurement location; however, there does not appear to be any pattern between type of bedrock and the measured resonance frequency.

Regression statistics were examined to determine whether outliers significantly affected the coefficient of determination from regression of known-bedrock-depth locations and H/V resonance frequency. Omission of two wells (LOG367744 and LOG467614) with substantial differences between the actual and estimated depth to bedrock improved the coefficient ($r^2 = 0.551$). However, the properties of these wells, the well sites, and (or) the horizontal/vertical spectra were not unusual enough from the rest of the known-bedrock-depth locations to eliminate them from the analysis. At each of these two wells, substantial amounts of clay were interspersed within the sand and gravel but no more so than at other wells used in the regression. The types of bedrock at the bottom of each well were shale and limestone, respectively. The sites were unremarkable in terms of ambient noise, and the resulting spectra were not obviously different from those of the other wells. Because there was no obvious reason to exclude these data, all known-bedrock-depth locations were included in the regression.

The HVSR method employed in this study yielded results that were, on average, within 14 percent of measured sediment thicknesses. However, the regression equation generated for this study was notably different from those determined for other studies (Fig. 3). In Equation 2 above, for example, the exponent b for this study was −0.63; in the previous studies cited herein, all values of b were less than −1.0 (Fig. 4; Ibs-von Secht and Wahlenberg 1999; Paraloai and others 2002). The exponent is the depth dependence of shear-wave velocity and, in this study, the exponent greater than −1 indicates that shear-wave velocity may decrease

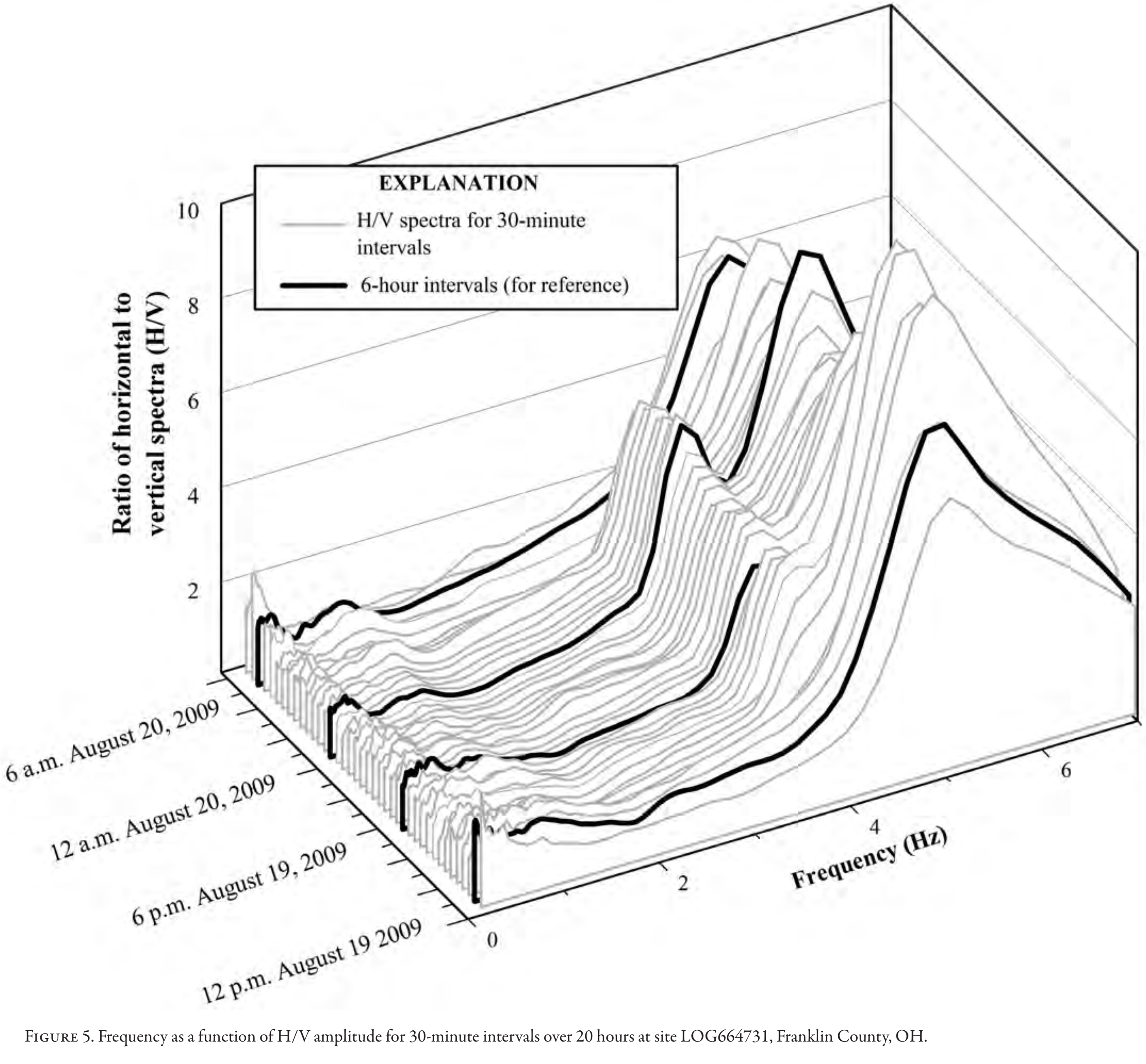

Figure 5. Frequency as a function of H/V amplitude for 30-minute intervals over 20 hours at site LOG664731, Franklin County, OH.

with depth. Without further exploration, this discrepancy is likely the result of heterogeneities in sediment type and thickness at some of the sites.

Another method to calculate a regression for known bedrock depths is by using Equation 1. From the known depths (Z) and resonance frequencies (f_r), the shear-wave velocity can be calculated for each site. Then, an average shear-wave velocity for all sites can be inserted in Equation 1 along with resonance frequencies at unknown locations to estimate sediment thickness. In this way, instead of calculating the shear-wave velocity function (a in Equation 2), the data are used to calculate an average shear-wave velocity, and an increase in shear-wave velocity with depth is implicitly assumed (where $b = -1$, Equation 2). For the data collected at the SWF, the average shear-wave velocity was 480 meters per second. This method was applied to the data in this study, and the coefficient of determination for the data was lower than when applying Equation 2 ($r^2 = 0.204$).

An analysis of the measurements made while a high-capacity production well was pumping and not pumping indicates no difference between the resonance frequency at the peak amplitude between pumping and non-pumping conditions, but these data showed a greater amplitude and, perhaps, a better resolution of the peak resonance frequency while the pump was on at that site. This finding suggests that, at areas where the natural seismic noise spectrum does not generate a clear peak, sources of anthropogenic ambient noise—such as pumping wells—may improve resolution of the peak resonance frequency. In future passive-seismic surveys where potentially large seismic noise sources exist, sources of anthropogenic noise also should be tested to see whether they aid in or detract from discrimination of the peak resonance frequency.

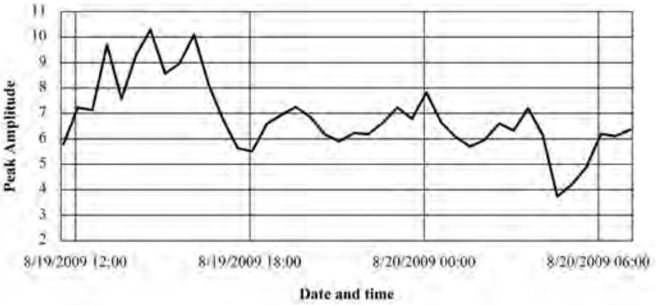

FIGURE 6. Peak amplitude of the H/V response over 20 hours on 19-20 Aug. 2009 at site LOG664731, Franklin County, OH.

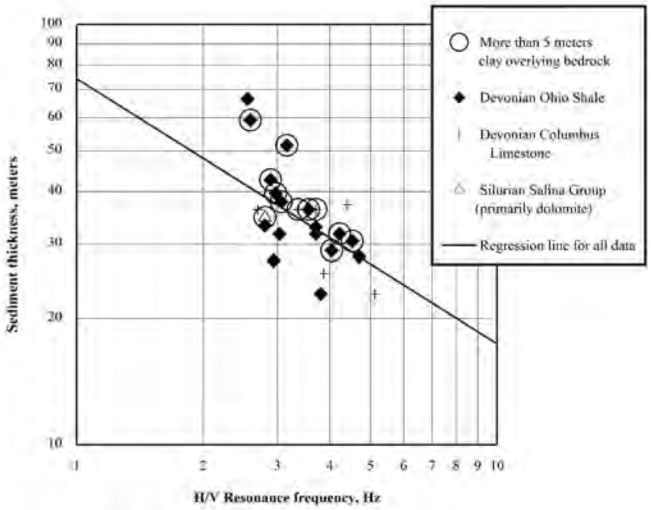

FIGURE 7. H/V resonance frequency and sediment thickness in relation to bedrock lithology and presence of clay greater than five meters, Franklin and Pickaway counties, OH.

The measurements made during the 20-hour test showed that, although smaller peaks changed shape and the amplitude of the peak resonance frequency changed with time of day, the resulting peak resonance frequencies are virtually identical for all time periods examined in this study. The amount of traffic on the nearby road had an effect on the amplitude, but not the resonance frequency or the results of the overall test, of the method in this setting. As noted above, if the noise spectrum does not provide a clear peak, then making measurements near roads with heavy traffic may actually improve results. In this study, no experiments were performed to examine the effects that distance from the source of noise (for example, a road) has on the H/V spectra.

More work needs to be done to understand issues related to the shear-wave velocity distribution, variability in site geology, and conditions under which the regression equations might be transferable to other sites where geology and lithology are similar. Multi-channel analysis of surface waves (MASW), a geophysical method that uses surface (Raleigh) waves to image near surface (one to 50 meters) shear-wave velocity structure, could be employed to investigate the variability of areal and vertical shear-wave velocities and compare with the HVSR results. Anthropogenic noise sources—specifically, traffic and a pumping well—increased the amplitude of the frequency curves, but they did not yield different sediment-thickness results from measurements with or without lesser ambient noise. The relatively quick and easy deployment of instrumentation and collection and interpretation of the data make the HVSR method a useful tool that hydrogeologists should consider when needing data regarding aquifer or sediment thickness.

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