ESTIMATION OF BEDROCK DEPTH USING THE HORIZONTAL-TO-VERTICAL (H/V) AMBIENT-NOISE SEISMIC METHOD

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Abstract

Estimating sediment thickness and the geometry of the bedrock surface is a key component of many hydrogeologic studies. The horizontal-to-vertical (H/V) ambient-noise seismic method is a novel, non-invasive technique that can be used to rapidly estimate the depth to bedrock. The H/V method uses a single, broad-band three-component seismometer to record ambient seismic noise. The ratio of the averaged horizontal-to-vertical frequency spectrum is used to determine the fundamental site resonance frequency, which can be interpreted using regression equations to estimate sediment thickness and depth to bedrock.

The U.S. Geological Survey used the H/V seismic method during fall 2007 at 11 sites in Cape Cod, Massachusetts, and 13 sites in eastern Nebraska. In Cape Cod, H/V measurements were acquired along a 60-kilometer (km) transect between Chatham and Provincetown, where glacial sediments overlie metamorphic rock. In Nebraska, H/V measurements were acquired along approximately 11- and 14-km transects near Firth and Oakland, respectively, where glacial sediments overlie weathered sedimentary rock.

The ambient-noise seismic data from Cape Cod produced clear, easily identified resonance frequency peaks. The interpreted depth and geometry of the bedrock surface correlate well with boring data and previously published seismic refraction surveys. Conversely, the ambient-noise seismic data from eastern Nebraska produced subtle resonance frequency peaks, and correlation of the interpreted bedrock surface with bedrock depths from borings is poor, which may indicate a low acoustic impedance contrast between the weathered sedimentary rock and overlying sediments and/or the effect of wind noise on the seismic records.

Our results indicate the H/V ambient-noise seismic method can be used effectively to estimate the depth to rock where there is a significant acoustic impedance contrast between the sediments and underlying rock. However, effective use of the method is challenging in the presence of gradational contacts such as gradational weathering or cementation. Further work is needed to optimize interpretation of resonance frequencies in the presence of extreme wind noise. In addition, local estimates of bedrock depth likely could be improved through development of regional or study-area-specific regression equations relating resonance frequency to bedrock depth.

Introduction

Determination of unconsolidated sediment thickness and the geometry of the underlying bedrock surface is an important component of many hydrogeologic studies, particularly those involving the development of conceptual and numerical models of ground-water flow and solute transport. One way to obtain this information is by drilling boreholes over the study area. While conventional borings provide detailed information proximal to the boring, drilling is expensive, and thus borehole information generally is sparse, with limited predictive value in the presence of strong geologic heterogeneity. It is therefore important to optimize boring locations to those areas of greatest interest to the study. Surface geophysical surveys (e.g., seismic, electromagnetic and electrical resistivity imaging, gravity, etc.) can help optimize the selection of drilling sites and augment drilling programs by providing spatially continuous estimates of subsurface physical properties that "fill the gaps" between borings and provide hydrogeologic insight where borings are not available. Some studies, however, neither require nor can support the expense of high-resolution continuous geophysical data, but would still benefit from an inexpensive method capable of rapidly providing a robust estimate of bedrock depth at a point. In this paper, we describe use of the novel, relatively simple, non-invasive, horizontal-to-vertical (H/V) ambient-noise seismic method proposed by Nakamura (1989) to determine the depth to bedrock at sites in Cape Cod, Massachusetts, and eastern Nebraska.

Method

In contrast to "active" seismic methods (e.g., refraction, reflection, or surface-wave), which use an artificial source such as an explosive charge or hammer blow to excite a seismic response from the subsurface, the H/V method is a "passive" method that uses three-component measurements of ambient seismic noise (microtremors induced by wind, ocean waves, anthropogenic activity, etc.) to determine and evaluate a site's fundamental seismic resonance frequency. The resonance frequency is determined through analysis of the spectral ratio of the horizontal and vertical components of ambient seismic noise. The H/V method has been used for microzonation studies to predict site response to earthquake seismicity (e.g. Nakamura,1989; Rial and others, 1992; Konno and Ohmachi, 1998) and as a method to estimate unconsolidated sediment thickness, map the bedrock surface, and infer fault locations (e.g., Ibs-von Seht and Wohlenberg, 1999; Delgado and others, 2000; Parolai and others, 2002).

For sites that can be approximated as a two-layer model (Figure 1), the seismic resonance frequency, f_{rn}, of the n^{th} mode is related to sediment thickness, Z:

$$f_{rn} = (2n+1)(V_s / 4Z), \qquad (1)$$

where V_s is the average shear-wave velocity in meters per second (m/s) of the sediment layer overlying bedrock, Z is given in meters, and f_{rn} is given in hertz (Hz) (Ibs-von Seht and Wohlenberg, 1999). The fundamental resonance frequency, f_{r0}, is given when n = 0, and higher-order modes of the resonance frequency are given by $n \geq 1$. Nakamura (1989) showed that the fundamental resonance frequency of a site can be determined from the ratio of the horizontal [$S(\omega)_{NS}$ and $S(\omega)_{EW}$] and vertical [$S(\omega)_V$] spectra of the ambient seismic noise, where ω is the angular frequency. Delgado and others (2000) compute the H/V spectral ratio as:

$$H/V\,(\omega) = \{[S^2(\omega)_{NS} + S^2(\omega)_{EW}] \,/\, 2S^2\,(\omega)_V\,\}^{1/2} \qquad (2)$$

It is important to note that the H/V method assumes a strong ($\geq$ 2:1) contrast in the acoustic impedance (product of material density and seismic velocity) of the bedrock and the overlying layer of sediments. The method is ineffective in geologic settings where this assumption does not hold, such as sites where there is gradational cementation, deep weathering, or strong heterogeneity.

The relation between sediment thickness, Z, and resonance frequency can be given by:

$$Z = a f_{r0}^{\ b} \tag{3}$$

where a and b are determined empirically from non-linear regression of f_{r0} data acquired at sites where Z is known (e.g., adjacent to boreholes). One advantage of equation (3) is that explicit measurement of V_s is not required. Ibs-von Seht and Wohlenberg (1999) and Parolai and others (2002) have published equations relating sediment thickness to resonance frequency based on correlation to borings in Germany (Table 1).

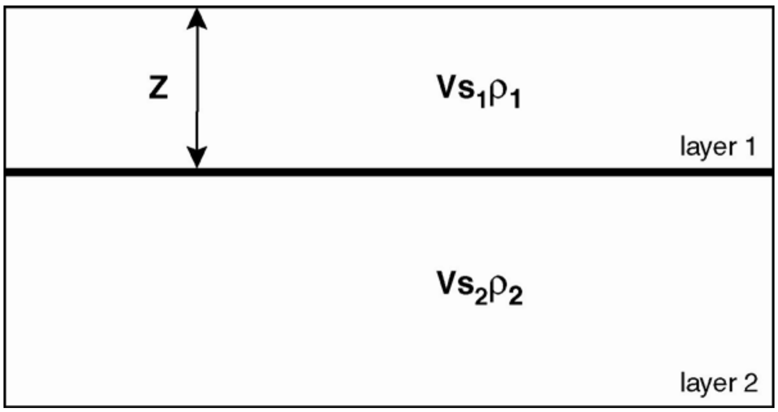

Figure 1: Conceptual earth model for H/V seismic method. The method assumes $Vs_2\rho_2 \geq 2Vs_1\rho_1$, where Vs_1 and Vs_2 are the shear wave velocities in layers 1 and 2, respectively, and ρ_1 and ρ_2 are the densities in layers 1 and 2, respectively. Z is the thickness of layer 1 (sediment).

Table 1: H/V Resonance Frequency- Power-Law-Function Fitting Parameters

Fitting Parameters		**Reference**
***a* (meters)**	***b***	
96	-1.388	Ibs-von Seht and Wohlenberg,1999
108	-1.551	Parolai and others, 2002

Field Study

The U.S. Geological Survey (USGS) conducted tests of the H/V seismic method at sites in Cape Cod, Massachusetts, and near the towns of Firth and Oakland, Nebraska, in the fall of 2007 (Figures 2 and 3). Ambient-noise seismic data were recorded at a minimum sampling frequency of 100 Hz using a

Guralp[1] model EDU three-component seismometer coupled to a field laptop computer (Figure 4). The seismometer used for this study can effectively record the seismic wavefield over a frequency range of 0.03-40 Hz. At the measurement location, the seismometer was placed on a ceramic tile coupled to the ground, which was free of loose soil and vegetation. During windy periods (wind speed in excess of about 5 m/s) the seismometer was protected from wind gusts by enclosing it inside an inverted, weighted bucket. Multiple records (typically two records, each 15 minutes long) were acquired at each site. Figure 5 shows a representative ambient-noise, three-component seismic record.

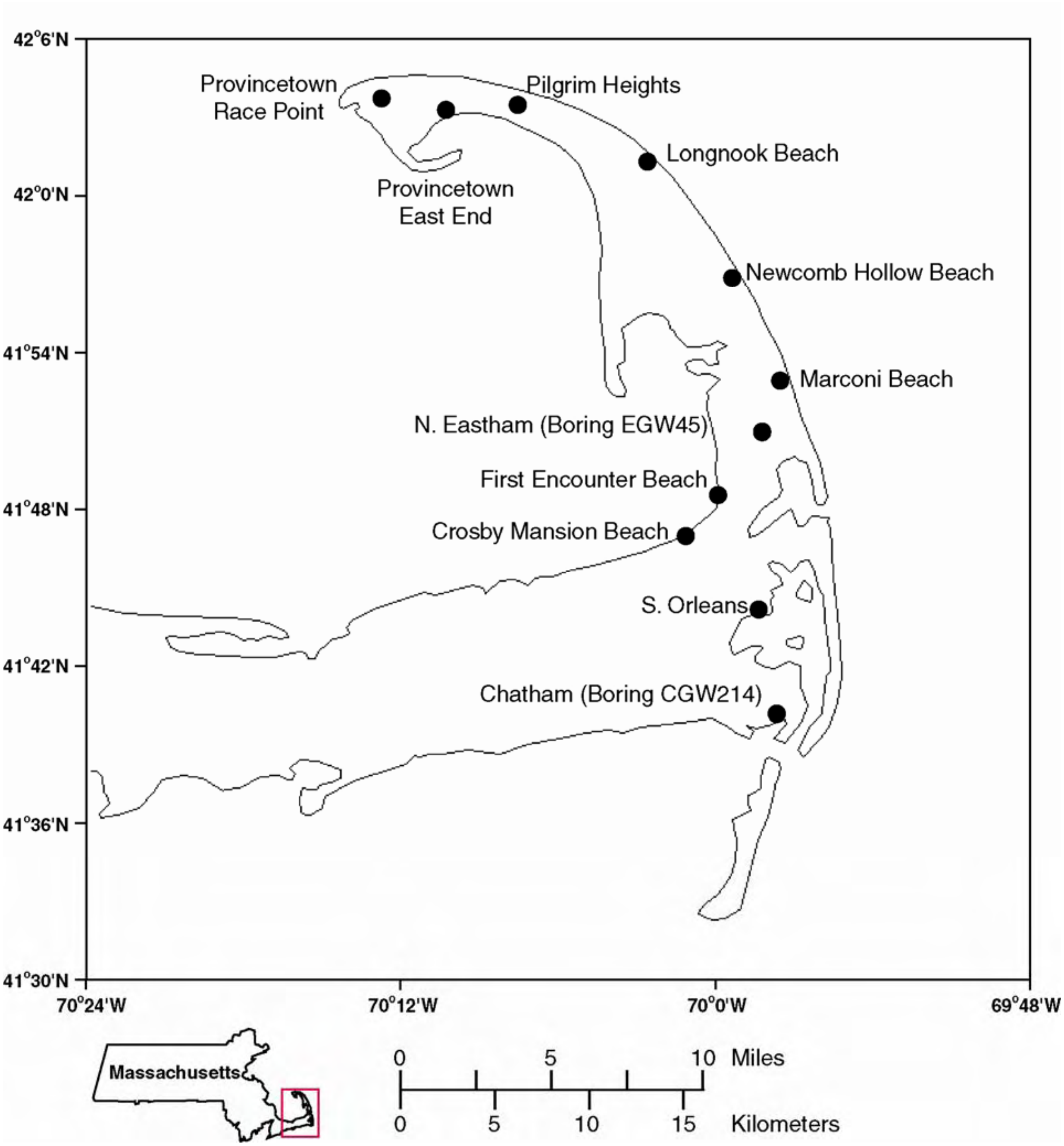

Figure 2: Cape Cod, Massachusetts, H/V survey sites.

[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

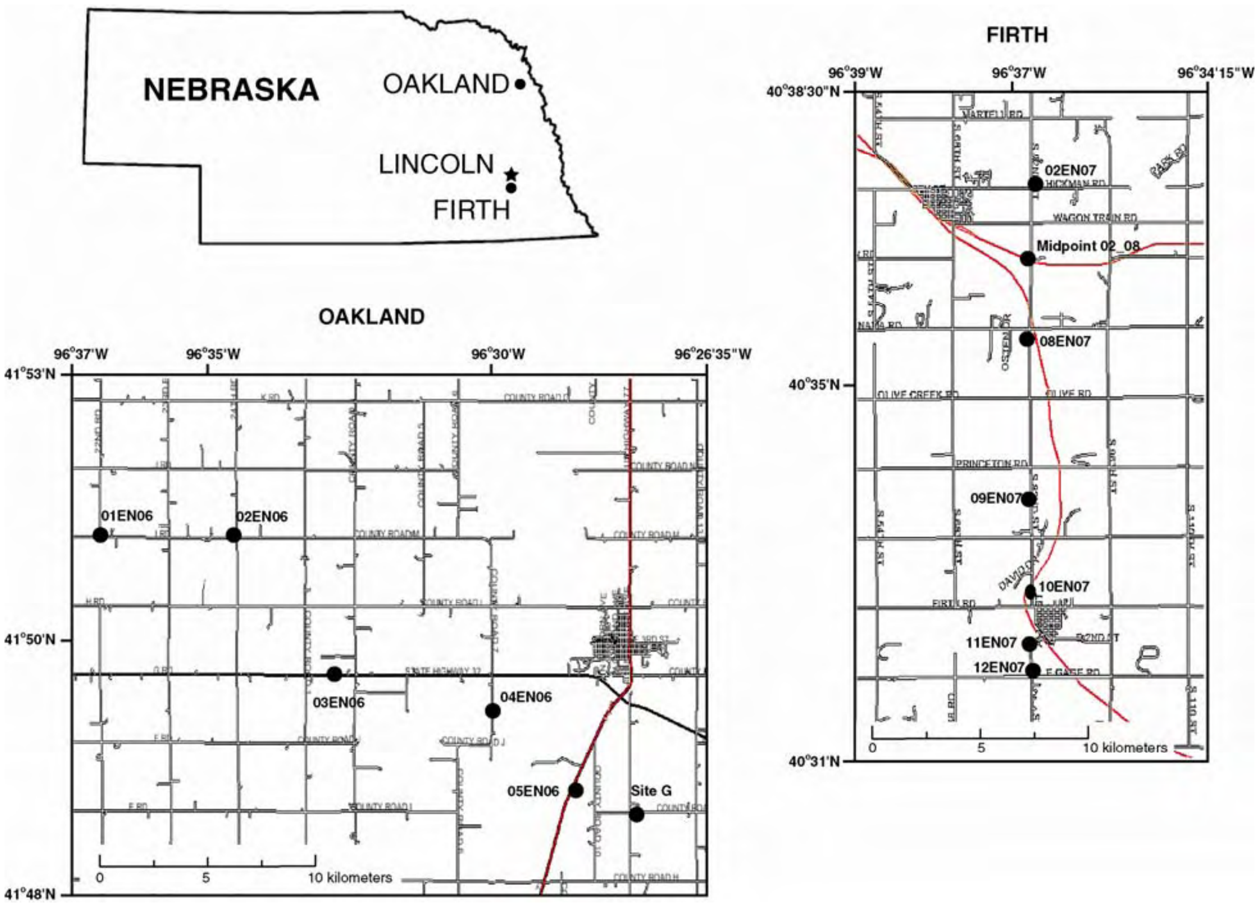

Figure 3: Nebraska H/V survey sites.

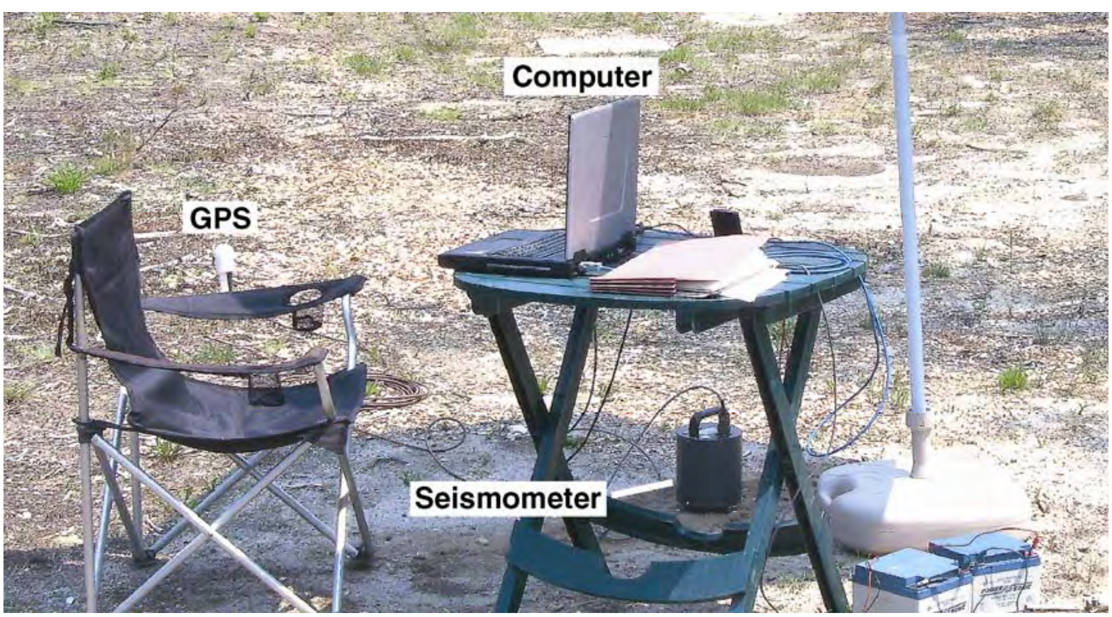

Figure 4: Three-component seismometer connected to field laptop for H/V seismic surveys.

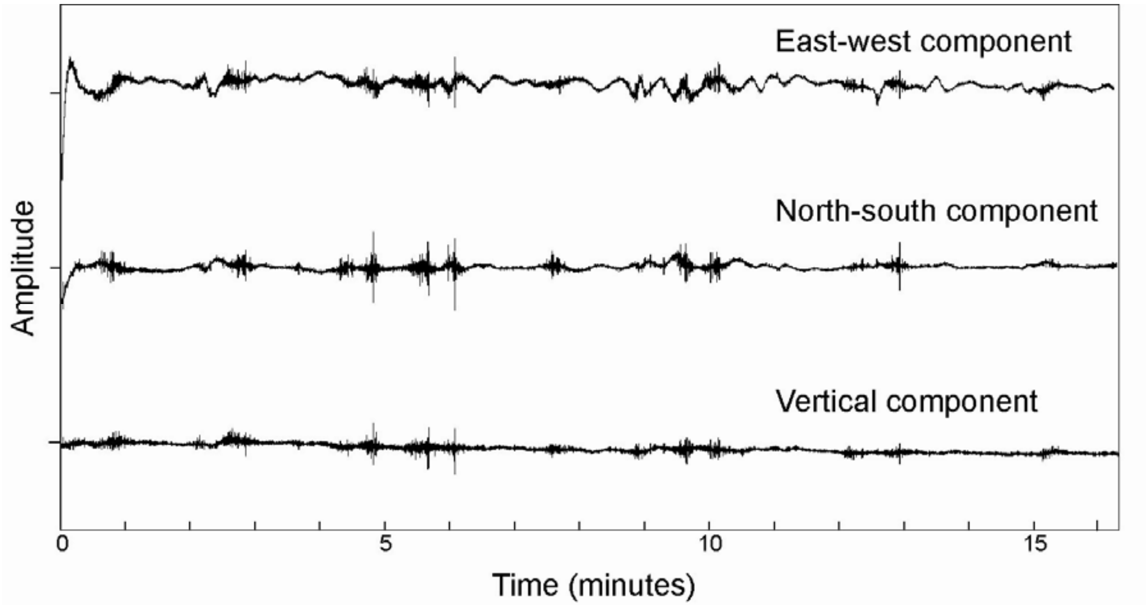

Figure 5: Representative 3-component ambient noise seismic records from Truro, Cape Cod, Massachusetts.

For the Cape Cod survey, 11 H/V measurements were acquired along an approximately 60-kilometer (km) long transect between Chatham and Provincetown, Massachusetts (Figure 2). At Cape Cod, glacial sediments overlie metamorphic rock, indicative of a high acoustic impedance contrast between the sediments and underlying bedrock. In eastern Nebraska, 13 H/V measurements were acquired along approximately 11-and 14-km transects near Firth and Oakland, respectively (Figure 3). In this area, glacial sediments overlie variably weathered sedimentary rock, which suggests the possibility of a low acoustic impedance contrast between the sediments and the underlying bedrock.

The data were analyzed using the *Geopsy* freeware software suite (http://www.geopsy.org/). For the Cape Cod surveys, the H/V resonance frequency for each site was determined by subdividing the record into 10- to 60-s time windows, which enabled exclusion of sections of record containing high levels of transient noise (e.g., noise from wind gusts or passing vehicles). The Nebraska survey data were acquired adjacent to busily trafficked roads in the presence of strong winds (>10 m/s). Because the Nebraska records contained high levels of transient noise, the variable window approach used for the Cape Cod data resulted in too few windows for analysis. Therefore, the H/V resonance frequencies for the Nebraska data were determined using a "brute-force" approach (which incorporated transient noise in the analysis) that subdivided the entire record into sequential 60-s time windows for analysis.

Results

Representative H/V spectral plots from the Massachusetts and Nebraska study areas are shown in Figures 6 and 7, respectively. Tables 2 and 3 show resonance frequencies derived from H/V analysis, interpretations of the depth to rock using the regression equations of Ibs-von Seht and Wohlenberg (1999) and Parolai and others (2002), and correlation of the results with other subsurface information. A profile of the bedrock surface interpreted from the H/V data from outer Cape Cod, Massachusetts, along with depth to rock obtained from boring logs (Masterson and Barlow, 1997) and seismic refraction surveys (Oldale, 1969), is shown in Figure 8. Profiles of the bedrock surface interpreted from H/V data along the Firth and Oakland transects in Nebraska, along with the depth to rock reported from borings, are shown in Figures 9 and 10, respectively.

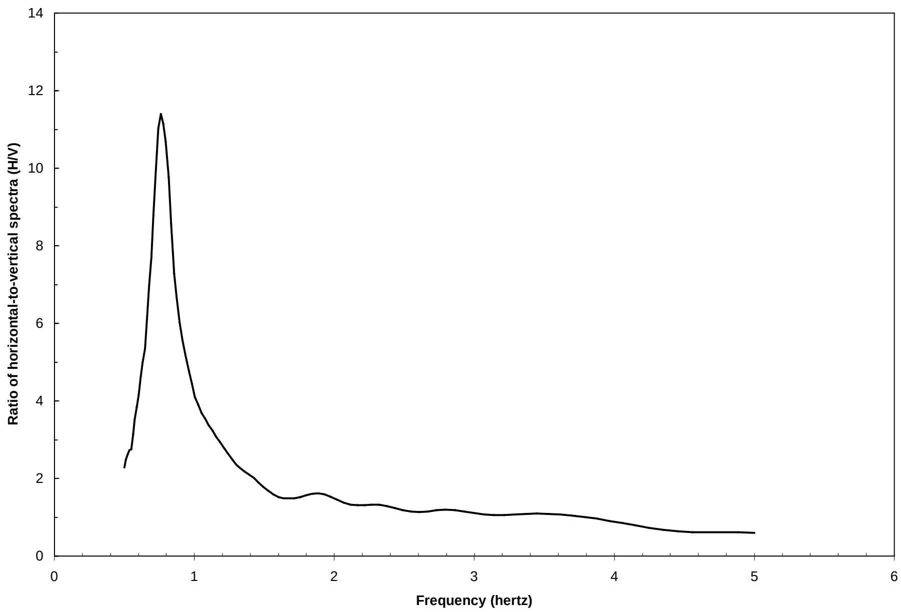

Figure 6: H/V spectral plot of ambient-noise seismic data from First Encounter Beach, Cape Cod, Massachusetts.

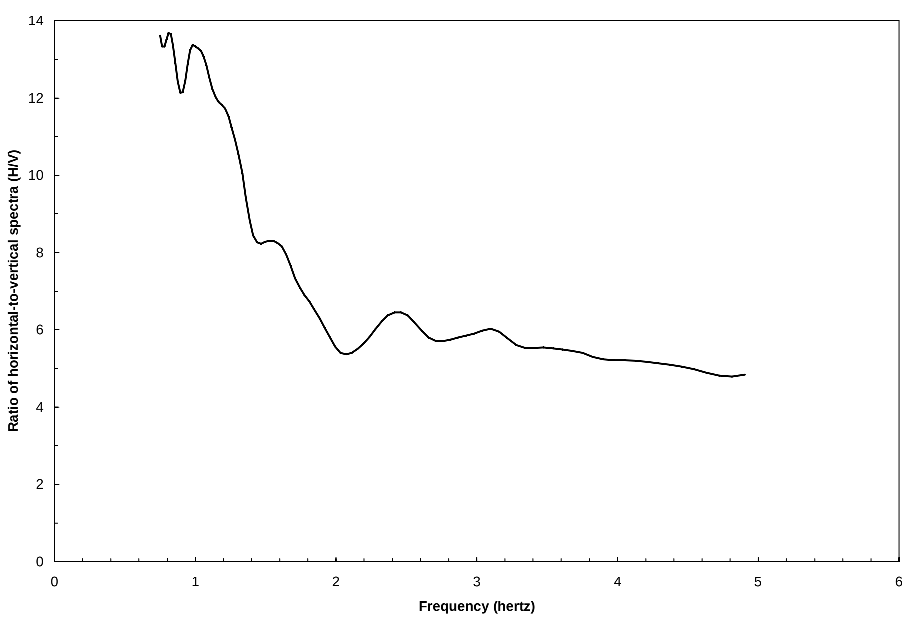

Figure 7: H/V spectral plot of ambient-noise seismic data from site 10NE07, Firth, Nebraska.

Table 2: H/V Resonance Frequency Seismic Survey Results – Outer Cape Cod, Massachusetts

[Boring depths from Masterson and Barlow (1997); Seismic-refraction depths after Oldale (1969); --, no data]

Site ID	**H/V Resonance Peak (hertz)**	**Interpreted Depth (meters)**		**Bedrock Depth from Boring (meters)/ Boring ID**	**Bedrock Depth Estimate from Seismic Refraction (meters)**
	10 to 60 second window	**Ibs-von Seht and Wohlenberg (1999)**	**Parolai and others (2004)**		
Survey Location: Outer Cape Cod, Massachusetts					
Chatham	0.814	128	149	112 /CGW214	125
S. Orleans	0.848	121	139	--	125
Crosby Mansion Beach	0.821	126	147	--	125
First Encounter Beach	0.769	138	162	--	125
N. Eastham	0.738	146	173	153 /EGW45	150
Marconi Beach	0.654	173	209	--	150
Newcomb Hollow Beach	0.664	169	204	--	150
Longnook Beach	0.598	196	240	--	200
Pilgrim Heights	0.555	217	269	--	200
Provincetown East End	0.602	194	237	--	175
Provincetown Race Point	0.611	190	232	--	150

Table 3: H/V Resonance Frequency Seismic Survey Results – Eastern Nebraska
[--, no data]

Site ID	H/V Resonance Peak (hertz)	Interpreted Depth (meters)		Boring Depth (meters)
	60 second window	Ibs-von Seht and Wohlenberg (1999)	Parolai and others (2004)	
Survey Location: Firth, Nebraska				
02EN07	1.24	71	77	27
Midpoint 02 to 08EN07	1.29	67	73	--
08EN07	2.21	32	32	35
09EN07	0.602	194	237	115
10EN07	0.615	189	229	115
11EN07	1.305	66	71	55
12EN07	0.933	106	120	85
Survey Location: Oakland, Nebraska				
Site G	1.85	41	42	50
05EN06	1.45	57	61	14
04EN06	1.24	71	77	29
03EN06	1.25	70	76	55
02EN06	1.32	65	70	58
01EN06	1.31	66	71	39

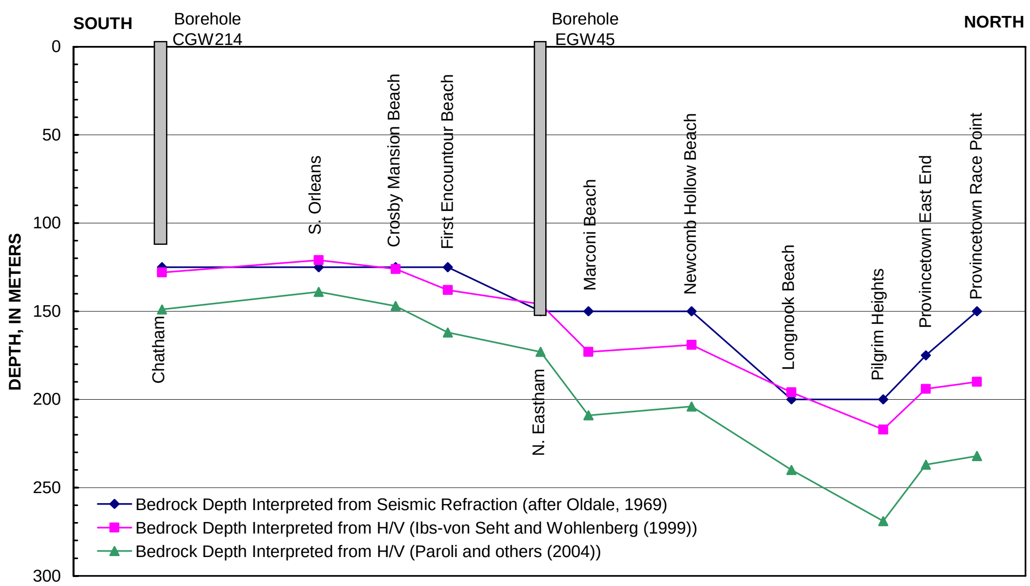

Figure 8: Profile of bedrock surface along outer Cape Cod, Massachusetts, interpreted from H/V results, and depth to bedrock interpreted from seismic refraction surveys and boring logs.

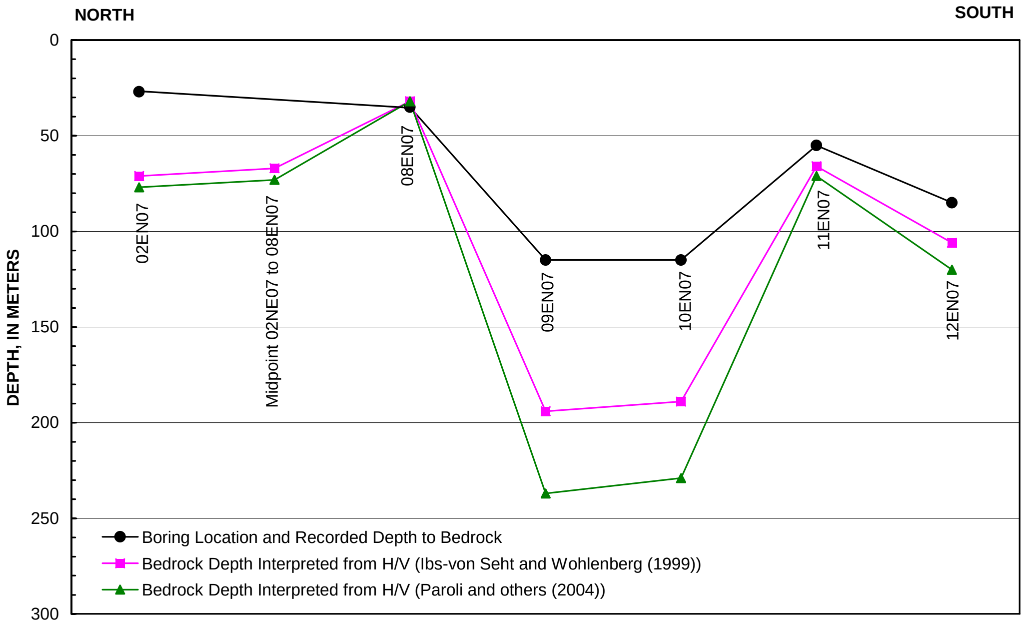

Figure 9: Profile of bedrock surface along transect near Firth, Nebraska, interpreted from H/V results, and depth to rock from adjacent boring logs.

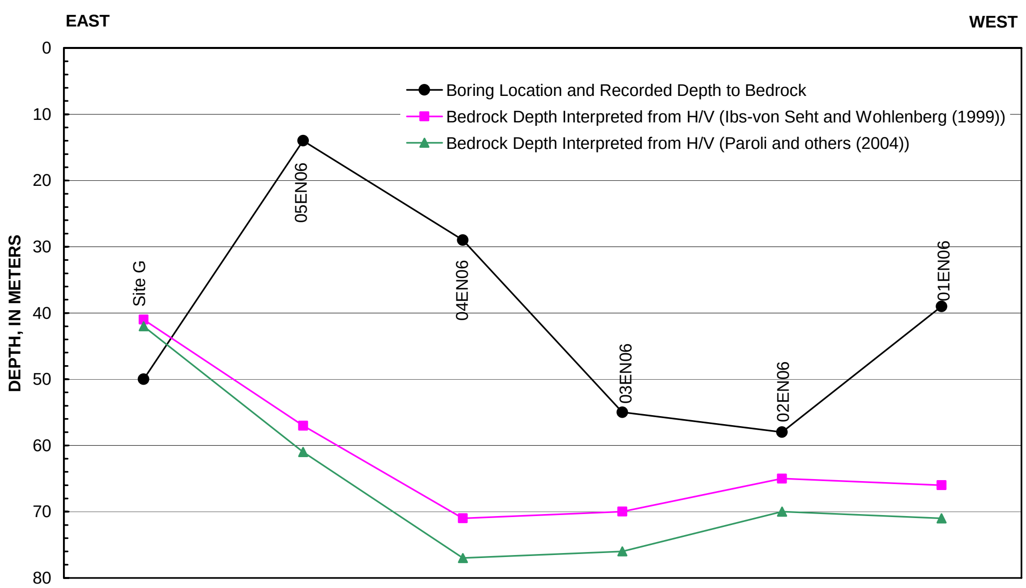

Figure 10: Profile of bedrock surface along transect near Oakland, Nebraska, interpreted from H/V results, and depth to rock from adjacent boring logs.

Discussion

H/V analysis of the Cape Cod, Masssachusetts, ambient-noise seismic data resulted in clear, easily identified resonance frequency peaks that show good correlation between decreasing resonance frequency and increasing depth to bedrock. The depth to bedrock interpreted from the H/V analysis is consistent with available drilling logs (Masterson and Barlow, 1997) and bedrock surface trends reported by Oldale (1969) from seismic refraction surveys.

The depth to bedrock was interpreted using two published regression equations (Ibs-von Seht and Wohlenberg, 1999; Parolai and others, 2002). Although both equations predict a similar bedrock surface, bedrock depths predicted by the Parolai and others (2002) equation are consistently deeper than indicated by other available information. In contrast, the equation by Ibs-von Seht and Wohlenberg (1999) produces an interpreted bedrock surface most consistent with the drilling logs and the seismic refraction surveys.

H/V analysis of the eastern Nebraska ambient-noise seismic survey data produced fairly subtle resonance frequency peaks in comparison to the Cape Cod survey results. In general, correlation between resonance frequency and reported depth to bedrock is poor. At Firth, the trend of the bedrock surface interpreted from H/V analysis is consistent with available drilling logs; however, both regression equations over-predict reported bedrock depths. At Oakland, neither the bedrock surface trend nor the depths to bedrock are consistent with reported bedrock depths.

Possible reasons for the differences between bedrock depth interpreted from the H/V data and the boring logs include (1) low acoustic impedance contrast between the bedrock and sediments, and (2) contamination of the seismic record by wind noise. One of the requirements for the H/V method is a sharp acoustic impedance contrast (>2:1) between the sediments and underlying rock. The Nebraska surveys were conducted at sites underlain by weathered shale. The presence of a weathered zone violates the assumption of a sharp acoustic impedance contrast, possibly decreasing site resonance frequency and interpreted depth to rock. With regards to noise, both Nebraska surveys were conducted in the presence of wind typical of the region. The Firth surveys were conducted during high winds (>10 m/s); for the Oakland surveys, conditions were initially calm, but wind increased during the survey period. Wind noise enriches the ambient-noise frequency spectrum with lower frequencies (particularly in the vicinity of trees, buildings, power lines, and other structures) that can degrade and obscure the interpretation of the resonance frequency. Wind effects can be minimized by conducting surveys on calm days, protecting the seismometer with an enclosure, and by establishing the measurement point as far as possible from nearby structures.

In this paper, resonant frequencies determined from H/V analysis were converted to bedrock depth using regression equations developed from studies in Germany. Although this approach produced reasonable results at Cape Cod, Massachusetts, using the equation published by Ibs-von Seht and Wohlenberg (1999), it is possible that local interpretations of bedrock depth would be improved by developing and applying regression equations consistent with the regional or local hydrogeologic setting.

Conclusions

The USGS applied the H/V ambient-noise seismic method to estimate the depth to rock at sites in Cape Cod, Massachusetts, and eastern Nebraska.

The ambient-noise seismic data from Cape Cod, Massachusetts, produced clear, easily identified resonance frequency peaks that correlate well with published depth to bedrock. The resonance frequency data were interpreted using two different regression equations developed from studies in Germany. Of the two, the equation by Ibs-von Seht and Wohlenberg (1999) produces estimates of bedrock depth that are most consistent with other available information.

In contrast, the ambient-noise seismic data from eastern Nebraska produced subtle resonance frequency peaks. Correlation of resonance frequency with bedrock depth is poor. Although the trend of the interpreted bedrock surface at the Firth, Nebraska site is consistent with drilling results, bedrock depths were consistently over predicted at both the Nebraska sites. Several factors may contribute to the differences in interpreted bedrock depth, including the presence of a weathered bedrock surface and the effect of wind noise on the seismic records.

Our results indicate the H/V ambient-noise seismic method can be used effectively to estimate the depth to rock at sites where there is a significant acoustic impedance contrast between the sediments and underlying rock. However, effective use of the method is challenging in the presence of gradational contacts (e.g., gradational weathering or cementation). Further work is needed to optimize interpretation of resonance frequencies in the presence of extreme wind noise. In addition, local estimates of bedrock depth likely could be improved through development of regional or study-area specific regression equations relating resonance frequency to bedrock depth.

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