

Study of the H/V spectral ratio method for determining average shear wave velocities in the Mississippi embayment

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ARTICLE INFO

Article history:

Received 21 October 2009

Received in revised form 26 January 2010

Accepted 31 January 2010

Available online 6 February 2010

Keywords:

Shear wave velocity

H/V

Microtremor

Site response

Mississippi embayment

ABSTRACT

The shear wave velocity (V_s) structure of the deep sediments in the Mississippi embayment is of interest to engineers and seismologists due to its influence on seismic wave propagation and site response during an earthquake. Although the shallow V_s structure (top 30 to 60 m) is generally well characterized, information on the V_s structure at greater depths (to 1000 m in some regions) is very limited. Past studies have developed relationships between the average V_s ($V_{s,AVE}$) of post-Paleozoic sediments in the embayment as a function of sediment thickness. One of these studies used converted body wave arrivals while the other used ambient noise measurements processed with the Horizontal-to-Vertical Spectral Ratio (HVSr) method. Interestingly, these two approaches yielded relationships that differed by about 25% to 30%. The objective of this study is to investigate the cause of the discrepancy between these relationships and identify the more reliable relationship for the V_s structure in the Mississippi embayment. Experimental measurements of ambient noise were performed at eleven deep soil sites in the Mississippi embayment and analyzed using the HVSr method. The results from the experimental study yielded $V_{s,AVE}$ values that were consistent with findings from the previous HVSr study. However, simulations of body and surface wave propagation performed using estimated full-depth V_s profiles at each site showed that the methodology used to develop the velocity–thickness relationship, specifically the approximate relationship used to relate site frequency, sediment thickness and V_s , produces an overestimation of the true $V_{s,AVE}$ for the profile by 25 to 30%.

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1. Introduction

The Mississippi embayment is a region of deep sediment deposits in the central United States which extends to depths of over 1000 m in some areas (Van Arsdale and Tenbrink, 2000). The shear wave velocity (V_s) structure of these sediments is of interest to engineers and seismologists due to its influence on earthquake site response (Park and Hashash, 2005; Cramer, 2006) and seismic wave propagation (Powell and Withers, 2009) in the embayment. Several studies have been performed to measure V_s profiles in the upper 30 to 60 m, however, knowledge of the deep velocity structure is very limited (Romero and Rix, 2001). Due to this limited information, a single reference V_s profile developed by Romero and Rix (2001) is often used to represent the deep structure of the embayment. One approach that has been used to assess the deep structure is to calculate an average shear wave velocity ($V_{s,AVE}$) value for the full depth of the post-Paleozoic sediments. Chen et al. (1996) deployed 40 portable three-component seismometers around the upper embayment and recorded more than 850 small earthquakes over a 34 month period. Using the time difference between direct and converted wave arrivals $V_{s,AVE}$ values were calculated for sediment

thicknesses ranging from 405 m to 860 m. The $V_{s,AVE}$ values obtained by Chen et al. (1996) ranged from 450 m/s to 670 m/s, as shown in Fig. 1.

Average shear wave velocity values were also estimated by Bodin et al. (2001) using a very different approach. Single-station ambient vibration (microtremor) measurements were performed at more than 100 sites around Shelby County, Tennessee using a three-component seismometer. The data were processed using the Horizontal-to-Vertical Spectral Ratio (HVSr) method (Nakamura, 1989) to estimate the fundamental frequency, f_0 , of each site. The HVSr spectra typically showed a strong peak in the period range of about 2 to 5 s, which could be clearly associated with the thickness of post-Paleozoic sediments. (A second frequency peak was also detected at most sites, but is not the subject of this paper.) Using the estimated depth to bedrock at each site, along with the fundamental frequency value, $V_{s,AVE}$ values were calculated for each site using an approximate relationship (equivalent uniform layer relationship). Interestingly, the relationship between $V_{s,AVE}$ and sediment thickness developed by Bodin et al. (2001) differed significantly from the relationship of Chen et al. (1996), as shown in Fig. 1. The values from Bodin's study were approximately 25 to 30% higher than the values developed by Chen (Bodin et al., 2001).

Although this difference was acknowledged and discussed in Bodin et al. (2001) no clear cause of the discrepancy was identified. Both of these relationships are still referenced in the literature (e.g. Williams et al., 2003; Gomberg et al., 2003; Powell and Withers, 2009), and it is not clear which should be considered the more reliable estimate. One possible

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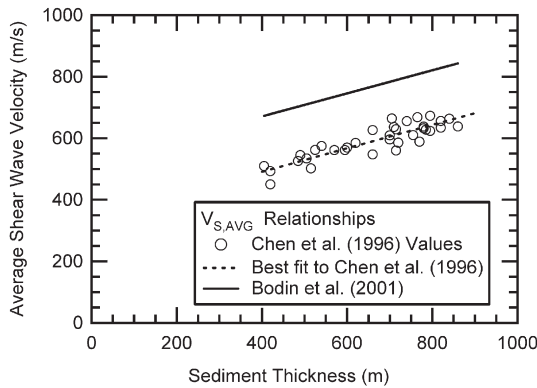


Fig. 1. Comparison of average shear wave velocity ($V_{s,AVE}$) versus sediment thickness relationships developed for the Mississippi embayment by Bodin et al. (2001) and Chen et al. (1996).

explanation for the difference is that the study areas sampled different portions of the embayment, although this is an unlikely reason for the large differences observed given the similar geology in the embayment. The objective of this paper is to investigate the reliability of the HVSR approach as a means to estimate full-depth, average shear wave velocity values. Experimental data analyses along with numerical simulations of surface wave and body wave propagation are used to meet the objective of this study, as described below.

2. Background on HVSR method

The Horizontal-to-Vertical Spectral Ratio (HVSR) method, also termed Nakamura's method, is a single-station approach using ambient vibration measurements to estimate the fundamental frequency, f_0 , of a site. The measurement is performed by recording ambient vibrations using a three-component station (two orthogonal horizontal components and one vertical component) for tens of minutes to over an hour depending on the expected site frequency (Bard and SESAME-Team, 2005). The spectra of the horizontal components and the vertical components are calculated, and the ratio of the combined horizontal spectrum to the vertical spectrum is determined. For site conditions where there is a strong contrast in velocity between the surface layer and a deeper material (velocity ratio of about 3.5 or greater) a peak will be observed in the HVSR plot that closely corresponds to the fundamental frequency of the site (as

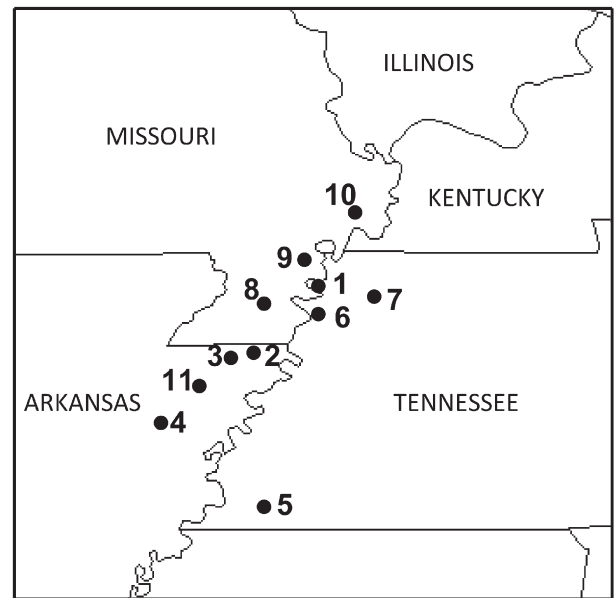


Fig. 3. Map showing the locations of the eleven sites where experimental HVSR measurements were performed for this study. Shaded region shows the approximate extent of the Bodin et al. (2001) study.

calculated for vertically propagating, horizontally-polarized shear waves propagating in the softer near-surface layer). This method has been used extensively in microzonation studies of cities around the world (i.e. Ibs-Von Seht and Wohlenberg, 1999; Delgado et al., 2000; Walling et al., 2009).

Although it has proven successful as a means to estimate site frequencies, there is still debate as to why it works. One explanation is that the peak in the HVSR plot can be explained as body wave energy, where source effects have been minimized by taking the ratio of the vertical and horizontal spectra (Ibs-Von Seht and Wohlenberg, 1999). A second explanation is that the ambient noise is dominated by Rayleigh waves and the peak in the HVSR plot is due to the particle motions of the Rayleigh wave, specifically a null value of the vertical component at a frequency that is very close to the fundamental site frequency, f_0 , for sites showing large shear velocity contrasts (Asten, 2003). Fig. 2 illustrates how the ratio of horizontal-to-vertical components of Rayleigh wave motion produces a peak that is very close to the lowest frequency peak of the one-dimensional transfer function for vertically-propagating, horizontally-polarized shear (SH) waves.

The primary use of HVSR measurements has been to estimate the fundamental site frequency, and hence differentiate between deep soft soil sites and shallow stiffer sites. In cases where the depth to bedrock is well established, the fundamental site frequency estimate

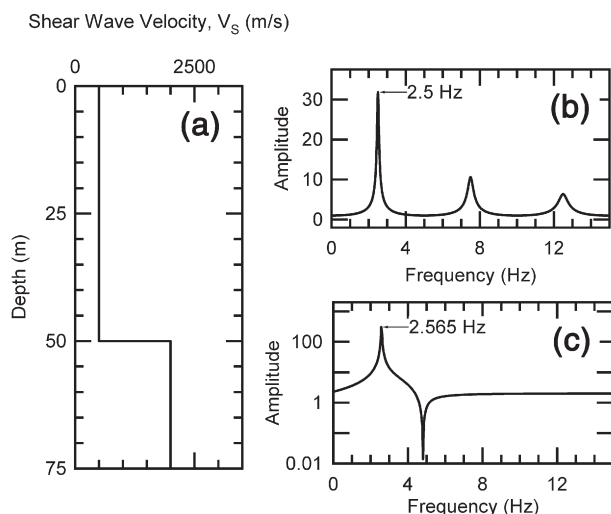


Fig. 2. (a) Velocity model of a soft layer overlying a stiffer half space (b) frequency peaks derived from transfer function of vertically-propagating, horizontally-polarized shear waves, and (c) HVSR of fundamental-mode Rayleigh wave.

Table 1

Location and site information for 11 measurement sites used in this study.

Site	Site location	Coordinates (degrees)	Seismic station	Depth to bedrock (m)
1	Mooring, TN	36.324 N 89.566 W	MORT	703
2	Yarbro, AR	35.981 N 89.915 W	–	783
3	Gosnell, AR	35.960 N 90.016 W	GNAR	820
4	Lepanto, AR	35.614 N 90.413 W	–	794
5	Memphis, TN	35.136 N 89.846 W	–	840
6	Tennemo, MO	36.161 N 89.579 W	TNMT	783
7	Glass, TN	36.263 N 89.288 W	GLAT	751
8	Braggadocio, MO	36.205 N 89.859 W	BRGM	714
9	Portageville, MO	36.450 N 89.628 W	PENM	586
10	East Prairie, MO	36.717 N 89.358 W	EPRM	451
11	Manila South, AR	35.784 N 90.147 W	MSAR	847

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