Surface Wave Measurements at a Deep Soil Site using Passive Surface Wave Energy

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ABSTRACT

Many seismically vulnerable cities in the United States and worldwide are located on very deep sediment deposits. Memphis, Tennessee, for example, is located on soil deposits that are over one thousand meters thick. Numerous critical transportation elements located in and around these cities are susceptible to high levels of ground shaking in an earthquake event. Recent studies have demonstrated the importance of measuring shear wave velocity (V_S) profiles over the full depth of the deep soil deposits for earthquake site response analysis. Traditional borehole methods, such as crosshole and downhole, are not economical over such great depths. Surface wave measurements are a non-intrusive means of determining V_S profiles. The need to actively generate low frequency surface wave energy has limited the depth of application of surface wave based methods. This paper presents results from surface wave measurements using passive noise at a deep soil site in the Mississippi Embayment region of the Midwestern United States. A two-dimensional circular receiver array was used to measure passive surface wave energy. Beamforming signal processing techniques were used to obtain surface wave velocity dispersion curves to wavelengths of 900 m. These results demonstrate the potential to apply inexpensive passive techniques for site characterization studies in regions with deep soil deposits.

INTRODUCTION

Many seismically vulnerable cities in the United States and around the world are located atop very deep soil deposits. In the Central United States, for example, Memphis Tennessee is located over the deep soil deposits of the Mississippi Embayment which reach maximum depths of over 1000 m (*1*). Underlying the embayment is the active New Madrid Seismic Zone (NMSZ) which was the source of the largest earthquakes in the continental United States. Numerous critical transportation elements are located in this region of the Midwest. Recent studies have demonstrated the need to characterize the properties of these deep soil deposits over their full depth range for seismic site response analysis (*2*). A vital part of the soil characterization is measurement of the shear wave velocity (V_S) profile. Conventional borehole methods such as downhole and crosshole measurements are not practical or economical over these great depths. For this reason, the near-surface (top 30 m) soil properties in the Mississippi Embayment are fairly well characterized, but there are few investigations extending to depths beyond 100 m (*3*). This is also the case for other deep soil deposits in seismically active regions around the United States, such as Salt Lake City, Utah.

Surface wave methods such as the Spectral-Analysis-of-Surface-Waves (SASW) method have been used extensively to obtain V_S profiles for near-surface site characterization studies (*4-6*). The depth of penetration of these active-source methods is limited by the ability to generate low-frequency, high amplitude energy. This study investigates the implementation of non-intrusive surface-wave methods using passive noise for characterization of deep soil deposits. The passive noise approach to surface wave measurements has been widely discussed in earlier studies by various researchers, for example, Capon (*7*), Tokimatsu et al (*8*), Zywicki and Rix (*9*), Liu et al. (*10*), Ohori et al (*11*), and Bozdag and Kocaoglu (*12*). The passive method requires in practice an array consisting of multiple low-frequency sensors (typically 12 or more) in a two-dimensional arrangement (typically circular). In this study, field measurements were conducted with a 200 m diameter circular array at a rural site in Tennessee. These methods have particular applicability to the Midwest, where numerous critical transportation systems transverse the deep sediments of the Mississippi Embayment. Inexpensive and reliable means to measure the properties of these deep soils are needed to better understand the seismic response of the region.

PASSIVE SURFACE WAVE MEASUREMENTS

All surface wave methods consist of: (1) measuring ground motions using an array of sensors, (2) generating a plot showing the velocity as a function of frequency (or wavelength) termed a dispersion curve and (3) using a forward modeling or inversion procedure to find a V_S profile that provides a match to the measured dispersion curve.

The passive source data processing approach used in this study is a frequency-wavenumber (*f-k)* beamforming method which utilizes a multi-channel array of receivers arranged in a two-dimensional array. The basic approach of the *f-k* method is to calculate for each frequency the array power output for a range of trial wavenumbers. The array output for each frequency is determined by shifting the phase of each receiver response based on pairs of trial wavenumbers k_x and k_y. The k_x and k_y wavenumber pair that provides the maximum power response at each frequency is used to determine the direction and velocity of the propagating wave. The procedure is then repeated over a range of frequencies of interest.

To perform this operation mathematically, the spatiospectral correlation matrix $\mathbf{R}(f)$ of the array is computed. The main diagonal elements of $\mathbf{R}(f)$ are the auto-power spectral densities for each sensors and the off-diagonal elements are the cross power spectra between any two sensors. Next a vector containing the phase shift information is calculated as:

$$\mathbf{e}(\mathbf{k}) = \left[\exp(-j\mathbf{k}\cdot\mathbf{x}_1), \exp(-j\mathbf{k}\cdot\mathbf{x}_2), \cdots, \exp(-j\mathbf{k}\cdot\mathbf{x}_N)\right]^{\mathrm{T}} \tag{2}$$

where $\mathbf{k} = (k_x, k_y)$ is the trial wavenumber pair and $\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_N$ are the sensor position vectors. The array output power $P_{FDBF}(f, \mathbf{k})$ is computed by multiplying the $\mathbf{R}(f)$ matrix by the above phase shift vector and summing the total power over all sensors, namely (*13*):

$$P_{FDBF}(f, \mathbf{k}) = \mathbf{e}^{\mathrm{H}}(\mathbf{k})\mathbf{R}(f)\mathbf{e}(\mathbf{k}) \tag{3}$$

where H denotes the Hermitian transpose. Equation (4) is used to calculate the velocity of the wave where $|\mathbf{k}| = \sqrt{k_x^2 + k_y^2}$.

$$V_R = \frac{2\pi f}{|\mathbf{k}|} \tag{4}$$

The number of receivers and size of the array will control the maximum and minimum wavenumbers that can be resolved (*14*).

SITE DESCRIPTION AND FIELD PROCEDURES

Measurements were performed at a site located in Mooring, Tennessee (Lat: 36.324N; Long: 89.566W; Elev: 84.1m) on private farmland, as shown in Figure 2. This site is located near a seismic station operated by the Center for Earthquake Research and Information (CERI) and is approximately 20 km north of the I-155 Mississippi River bridge crossing.

The passive surface wave testing used a 16-sensor circular array with a radius of 100 m, as illustrated in Figure 2. Time domain data were recorded at each of the 16 receivers at a sampling rate of 32 samples per second for 30 minutes. For the analysis, the time domain data from each sensor is segregated into 28 blocks, each of which is 64 sec long. Then the spatiospectral correlation matrices $\mathbf{R}(f)$ calculated from the individual blocks are averaged to obtain the final $\mathbf{R}(f)$.

CALCULATION OF PHASE VELOCITY DISPERSION CURVE

The passive measurement data was used to calculate a phase velocity dispersion curve for the site. The spatial correlation matrix $\mathbf{R}(f)$ was computed using the procedures described by Zywicki (*15).* As an example, the *f-k* spectrum for a frequency of 1 Hz is shown in Figure 3. The components of the wavenumber vector determined from the maximum spectral power are k_x=0.00709 rad/m, k_y=0.00047 rad/m. The corresponding phase velocity is 885 m/s.

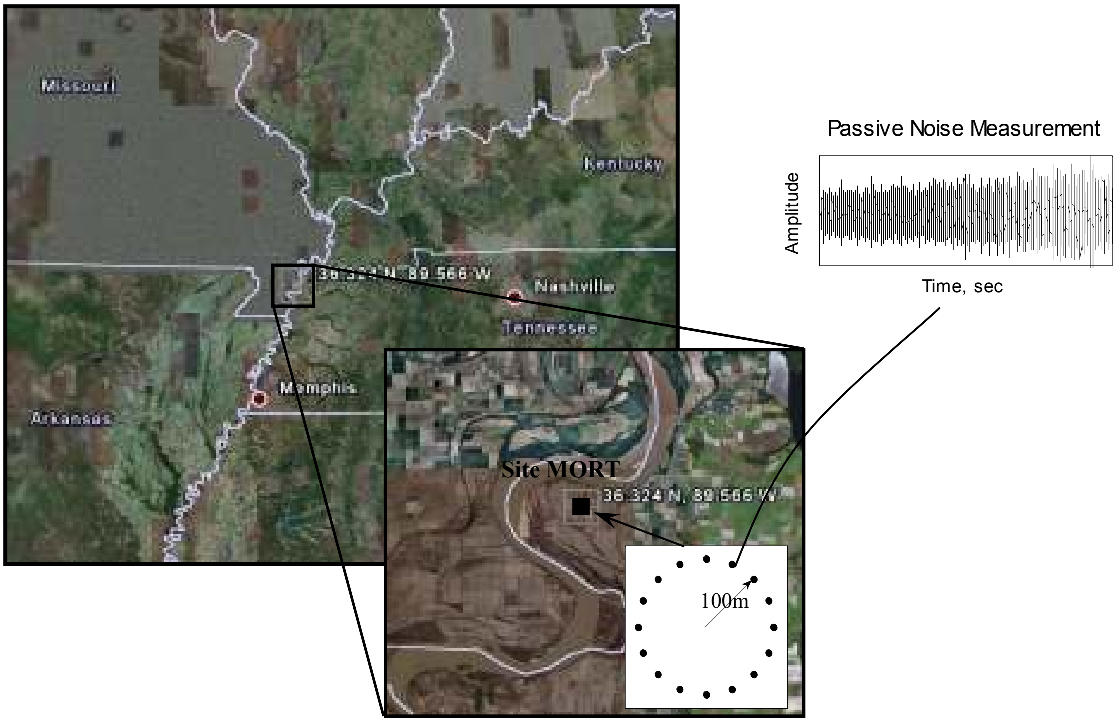
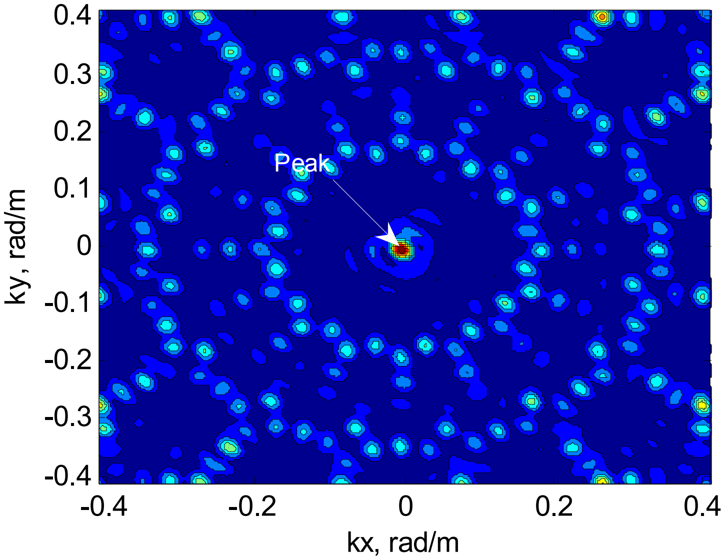


FIGURE 2 Site location at Mooring, TN (map from Google Earth).



$$k_x = 0.00709, k_y = 0.00047$$

$$|\mathbf{k}_{\mathbf{peak}}| = \sqrt{k_x^2 + k_y^2} = 0.00711$$

$$f = 1\,\mathrm{Hz}$$

$$V_R = 2\pi f / |\mathbf{k}_{\mathbf{peak}}| = 885\,\mathbf{m/s}$$

FIGURE 3 Example of an *f-k* spectrum of the circular array $f = 1\,\mathrm{Hz}$.

Figure 4 presents the surface wave velocity dispersion curve generated from the passive surface wave measurements. Data was obtained over a wavelength range of about 100 to 900 m. Because the intent of the study was to examine the ability to measure long wavelength surface wave energy, dispersion curves with shorter wavelengths were not attempted with the passive technique. Active source surface wave measurements were also conducted at this site using a low-frequency servo-hydraulic vibrator. The active and passive surface wave dispersion curves agreed well in overlapping wavelength regions, as shown in Figure 4.

V_S profiles have not yet been developed from this dispersion data. In general, V_S profiles can be determined to a depth equal to approximately one half of the maximum wavelength (*16*). This implies that the V_S profile can be determined to a depth of approximately 450 m using passive noise measurements and a 200-m diameter array.

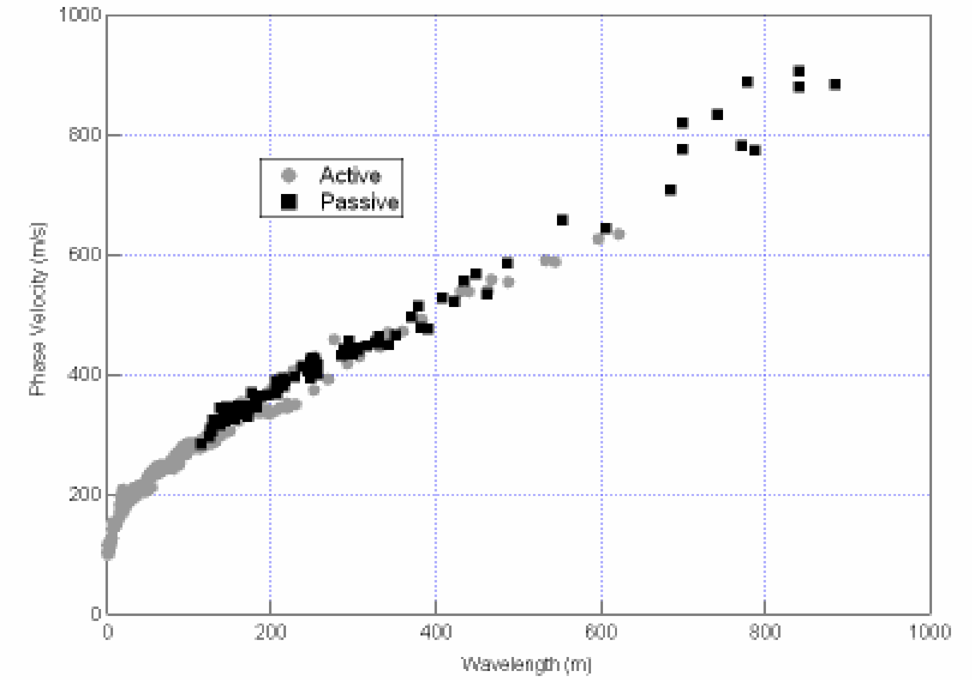


FIGURE 4 Comparison of dispersion curves obtained from active and passive surface wave methods

CONCLUSIONS

Passive energy surface wave velocity measurements were performed at a deep soil site in the Mississippi Embayment region of the Midwestern United States. Dispersion data collected using a 2-D array and passive energy yielded a dispersion curve that was consistent with active source results and provided data to wavelengths of approximately 900 m. The results from this study demonstrate that the passive source method can provide surface wave dispersion data that can be used to inexpensively develop deep (400-500 m) V_S profiles. The V_S profiles are critical parameters for predicting seismic site response at deep soil sites.

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