Site Characteristics by a Joint Surface Wave Investigation

SHI Lijing, TAO Xiaxin, Robert Kayen, SHI Hailiang

ABSTRACT

The S-wave velocity structure plays an important role in site condition effects. Two kinds of surface wave investigation methods, the Microtremors Array Measurement (MAM) and the Spectra Analysis of Surface Waves (SASW) method, were jointly conducted last October for site characteristics in Tangshan region, China. These two methods have similar theoretical bases and also a noteworthy difference. The dispersion curves are independently computed from the data acquired by two methods, the curves at each site are compared. The results show that MAM predominates at low frequency range from 2 to 12 Hz whereas the SASW at higher frequency up to 100 Hz. The S-wave velocity structures at one site are inverted from the two dispersion curves. The profiles are compared with that from borehole measurement. To validate the effect of the difference on the site response, the corresponding ground response characteristics from the three profiles calculated.

INTRODUCTION

The variety of S-wave velocity with the depth, namely S-wave velocity structure, which reflects indirectly the stiffness of sediment, impedance ratio and distribution of different soil and has a great effect on the estimation of site soil dynamic behavior, is the absolutely necessarily basic data for rating site condition effect. So it’s necessary and paramount to detect site S-wave velocity structure.

Microtremors are an assemblage of body and surface waves that originates in space and time from a wide variety of sources, and propagates over a wide frequency band. It is a continuous low amplitude wave "field" and in genera most of the wave energy is transported as surface waves (Toksöz and Lacoss, 1968). If the dispersive property of the surface wave contained in microtremors is analyzed, it can provide good help to understand site S-wave velocity structure. Since 80s, great breakthroughs have been made in inversion of site S-wave velocity structure by array observation of long period microtremors. After microtremors are observed with array and observation records are analyzed by signal processing methods, the S-wave velocity structure can be determined from array records by inversion methods. In many countries, especially in Japan, the microtremors array method (MAM) has gained many applications.

The Spectra Analysis of Surface Waves (SASW) method is another non-intrusive method for estimating the S-wave velocity structure that also based on the dispersion property of Rayleigh surface waves which means that most of the Rayleigh surface wave energy exists within one wavelength of depth and in layered media the propagation velocity of surface wave depends on the frequency of the wave because waves of different wavelength sample different parts of the layered media. Both MAM and SASW method capture the Rayleigh wave on the ground surface and neither needs drilling holes. So they are economical and have no environmental problems.

SHI Lijing, Institute of Engineering Mechanics, China Earthquake Administration, Harbin, 150080, China
TAO Xiaxin, College of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, China
SHI Hailiang, College of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, China
Their theoretical bases are similar, but both their observation methods and analysis methods have noteworthy differences because the sources of surface wave they observed are different. MAM records the environmental noise whereas SASW records the surface wave generated by active source. So they can also be called active method and passive methods and have their own advantages and shortcomings. The records of SASW have determined sources so it is relatively easy to analyze. It’s easier to produce high frequency components for the active sources of SASW and result in a highly detailed-shear wave model of the ground. But if the low frequency components are to be generated, the shaker will be very cumbersome and it brings some difficulties to testing in-situ. MAM needs no active sources so the testing in situ is easy. But the sources of microtremors are very complicated so more powerful analysis method is required.

In order to study the difference of the two methods, we deployed observation arrays for MAM and SASW in 26 sites in Tangshan, China. In this paper, the Rayleigh wave dispersion curves analyzed by MAM and SASW method are compared at these sites. And the S-wave velocity structures inversed from the dispersion curves obtained by different methods and corresponding response spectral are compared at one site.

OBSERVATION SYSTEM AND ANALYSIS METHOD

Microtremors Observation

The array observation system of microtremors is composed 4 sets of three-component seismometer and a 12-channel Data-Collection and Analysis System (including signal sampler, AD converter and recorder). The seismometer is DLS-200 force-balanced accelerometer (Figure 1). The sensors are all made in Institute of Engineering Mechanics, China Earthquake Administration. Its working frequency is very broad, ranging from 0.01Hz to 80Hz. Its magnitude frequency characteristic is shown in Figure 2. The sensors have a maximum sensitivity of 2000 v/g. And the natural frequency of the sensors is 80Hz. The 12 channels Data-Collection and Analysis System that is composed of hardware and software is researched and produced by Beiao Corporation, the sampling frequency of which is 32Hz～100KHz. All channels that are connecting to the LPT (EPP model) of the portable computer start record at the same time; therefore, there are no phase differences. In the time domain, it can display data, reading, magnify or shrink figure of the wave and also can display by pages or only one channel. In frequency domain, it can calculate Power Spectra and Fourier Spectra, which can be smoothed by spectral window (rectangular window, hanning window, hamming window).
The first and chiefly task is to extract dispersion curve of Rayleigh wave from microtremors array records. The frequency-wavenumber method (FK) and the Spatial Auto-correlation method (SAC) are the two methods that are usually used to analyze the dispersion curve of Rayleigh wave. By SAC method, the configuration of the array is limited to circle and only 4-6 observation stations are needed. By FK method, the configuration of the array is flexible, but more observation stations are needed and the frequency range obtained is narrower using same size array. Devoted to inversion of shallow velocity structure and wishing gain dispersion curve for wider frequency range, we select SAC method to analyze microtremors records.

The SAC method was first developed by Aki. In this method, microtremors is treated as a stochastic process. And isotropic waves that come from random directions and at each frequency, the wave energy propagates with only one (scalar) velocity are assumed. Phase velocities are determined by averaging signal coherency between multiple observation points in an array of receivers, with no consideration of the direction (or distance) to the source. A circular array of geophones placed equidistant from a single, central geophone is deployed to obtain Rayleigh wave samples propagating from a wide range of azimuthal angles. According to Aki, if waves have dispersion characteristics like surface wave, spatial auto-correlation coefficients among waves must be a function of phase velocity and frequency. Further, Spatial auto-correlation coefficient \( \rho(r, \omega_0) \) with angular frequency \( \omega_0 \) and distance \( r \) can be related to Bessel function of the first kind of zero order \( J_0(x) \) as follow.

\[
\rho(r, \omega_0) = J_0(k_0 r) = J_0\left(\frac{\omega_0}{C(\omega_0)} r\right)
\]

Here, \( C(\omega_0) \) is the Rayleigh wave phase velocity, \( \frac{\omega_0}{C(\omega_0)} \) is wave-number. We consider the vertical-component of microtremors as Rayleigh wave. The correlation coefficients between the center station \( O(0, 0) \) and other stations \( B_i(r_i, \theta_i) \) can be calculated by the following formula.

\[
\rho_{O B_i}(r, \omega_0) = \frac{f_o \cdot f_{\theta_i}}{(f_o \cdot f_{\theta_i})^{0.5}}, \text{ i}=1, 2, m
\]

Azimuthally averaged coherencies can be computed by averaging the coherencies for all geophone pairs in the array having the same spatial scalar separation. So the coefficients between different stations can be averaged and by formula (1) we can obtain following formula.

\[
\overline{\rho}(r, \omega_0) = \frac{1}{N} \sum_{i=1}^{N} \rho_{O B_i}(r, \omega_0) = J_0\left(\frac{\omega_0 r}{C(\omega_0)}\right)
\]

First, the records can be filtered by very narrow band-pass filter with a series of center frequency and then the spatial auto-correlation coefficients are calculated. Thus the Rayleigh wave phase velocity can be obtained by above formula.

**SASW Observation**

The Spectral Analysis of Surface Waves (SASW) method is another seismic tool to evaluate the stiffness characteristics of soil deposits. SASW is especially useful for profiling gravelly deposits.
where sampling is difficult and penetration tests fail to characterize or quantify soil properties. The spectral analysis of surface wave is introduced by Stokoe and Nazarian and has been widely applied to many engineering problems over the last couple decades. During the SASW test, field measurements of surface wave dispersion are recorded using multiple arrays of seismometers. Our field configuration for SASW uses a computer-controlled electromechanical shaker as the mid-point of the array (i.e., Common-Source Midpoint), and four seismometers arrayed in pairs of two and aligned in opposite directions of the source. We use an APS-Dynamics shaker that can produce sinusoidal waves from to 1-1000 Hz (Figure 4). Using such a shaker-source allows for elevated signal-to-noise ratio as compared with a conventional random-noise hammer source. We use the shaker to produce controlled vertical vibrations between 1-150Hz.

The 1-Hz Kinemetrics receivers (Figure 5) we use are designed for capturing vertical motions and cover the frequency range of interest in the active-source surface-wave test. For each source-receiver configuration, surface waves are generated by the shaker, whose motion is controlled by an output waveform from the spectral analyzer. An amplifier boosts the analyzer signal in order to drive the electromechanical motor in the shaker. The receivers measure the waves and a fast Fourier transform (FFT) is performed on each of the four receiver signals. In near-real-time, the linear spectra, cross power spectra, and coherence are computed. The ability to perform near real-time frequency domain calculations and monitor the progress and quality of the test allows us to adjust various aspects of the test to optimize the capture of the phase data. These aspects include the source-wave generation, frequency step-size between each sine-wave burst, number of cycles-per-frequency, total frequency range of all the steps, and receiver spacing.

The common receiver midpoint geometry of Nazarian and Stokoe [1984] typically used in SASW testing is not used with our system, given the weight of the electromechanical shaker. Rather, we adopt common source-midpoint geometry. That is, we place the source at the centerline of the survey so that the forward and reverse direction dispersion curves were equidistant from the source for each given array spacing. Several different spacing of receivers are used in the field, and the dispersion curves for each spacing, both in forward and reverse directions, are merged to build a site-dispersion plot. Spacing of receivers steps geometrically from 1 meter to 24 or 32 meters. The two seismometers are separated by a given distance, $d$, and the source is usually placed at a distance of $2d$ from the first seismometer.

After record the ground motion, the cross-spectrum of records from the two receivers can be computed.
\[ S(f) = \frac{1}{n} \sum_{i=1}^{n} [X_i(f) \cdot Y_i^*(f)] \]  

(4)

where \( S(f) \) = cross-spectrum of \( x(t) \) and \( y(t) \), \( X(f) \) = Fourier Transform of \( x(t) \), \( Y^*(f) \) = complex conjugate of the Fourier Transform of \( y(t) \). The phase information as a function of frequency can be extracted by following equation.

\[ \Phi = \tan^{-1} \left( \frac{\text{imag}[S(f)]}{\text{real}[S(f)]} \right) \]  

(5)

We can see the phase calculated from above equation is bounded between +180 and -180. So it need be unwrapped. If the given pair of sensors is a distance \( D \) apart, then the phase velocity is given by

\[ V_R(f) = \frac{2\pi f \cdot D}{\Phi} \]  

(6)

where \( V_R \) is phase velocity. By changing receivers spacing and the frequency range of the impulse, a broad range of dispersion curve can be explored.

There also is one noticeable problem that not all the dispersion points calculated are valid. The root mean square coherence is used to measure of signal quality. It is calculated by following equation.

\[ \gamma^2 = \frac{|S_{xy}(f)|^2}{S_{xx}(f) \cdot S_{yy}(f)} \]  

(7)

where \( S_{xy}(f) \) is Cross power spectrum of \( x(t) \), \( S_{xx}(f) \) and \( S_{yy}(f) \) is Auto power spectrum of \( x(t) \) and \( y(t) \) respectively. In general, if the root mean square coherence with a value of 0.95 or higher, the dispersion points may be defined valid or may be defined invalid.

**Joint Observation Scheme and Sites**

![In-situ MAM and SASW test](image)

Figure 6  In-situ MAM and SASW test
In order to compare the two methods, we place two microtremors receivers at the same place with the two SASW receivers in the same direction (see Figure 6). That is the spacing of SASW receivers equal to the radius of microtremors array. And the radius of microtremors array changes with spacing of SASW receivers steps geometrically from 2 meter to 4, 8, 16, 24 meters. And the other two microtremors receivers will be place to compose a circle array. By this joint observation scheme, we not only can study the influence of different analysis methods under the same kind source (passive or active) but also can study the influence of different kind sources with the same signal processing method.

For SASW observation system, only the dispersion curves are saved. But we record both forced vibration and microtremors with the microtremors observation system for further studies.

A total of 26 sites were investigated (see Fig. 7). The red dots show the location of observation sites. Figure 2 shows the locations of 4 test sites in Lutai. Both tests have been carried out at each test site. Each surface wave test site successfully reoccupied the penetration site of Zhou and Zhang (1979). These sites located in different intensity area of the Tangshan Earthquake. 12 sites located in Intensity and 10 in Intensity, 4 in Intensity. 18 sites are liquefied and 8 un liquefied during the Earthquake. After the Tangshan Earthquake, three tests has been conduct in these test: (1) Borehole sampling for determining the physical properties of soils; (2) standard penetration tests and (3) static cone penetration tests. So for all the 26 sites, there are detailed geotechnical information including type of soil, data of standard penetration test and static cone penetration test, water content, density, data of particle analysis, etc. All these data and information can be found in reference (Liu Huixian, 2002). But unfortunately there is no S wave velocity structure data and the location is not record in detail. So in order to conduct MAM and SASW test, we made great efforts to find the right place of the sites. After our test, all the sites were relocated by GPS. So it is easy to find for future study.

Lutai is one city that we test 4 sites (see Figure 8) there, 2 liquefied and 2 un liquefied. Located in the southwest part of Tangshan city, Lutai district is 48 km from the epicenter of the Tangshan earthquake of M=7.8. However, this district, being seriously damaged, is an intensity anomaly of IX in the area of intensity of VIII. From the statistics of Ninghe county government, 87% of the industrial and civil buildings were heavily damaged; some completely collapsed. Subsoil liquefaction was one of the main factors causing such tremendous losses. Sand boils induced large scale ground surface settlement at the center of Lutai district. From November 1976 to May 1977, surveying of Lutai soil and geotechnical investigation of its liquefaction were carried out. A static cone penetration test is mainly used for in-situ testing. Standard penetration test is only applied to sandy loam of layer III-I, V and silt of VII in part boreholes.
We were successful in investigation of 26 sites in Tangshan City, Hebei and Lutai City, Tianjin. At each site, we make paired-measurements of surface wave dispersion characteristics by active harmonic SASW and passive microtremor array methods. At each site, 5 linear arrays of different distance between two adjacent sensors were deployed for SASW testing and 2-3 2-D arrays with different radius for Microtremors observation. Totally 63 arrays were deployed and 1440 vertical and horizontal records were obtained.

DISPERSION CURVES COMPARISON

For MAM, we used 4096 or 819.2-second data for the SAC analysis. First all the microtremors records are divided into 4096 or 81.92-sec data without heavy artificial noises. The application of the SAC analysis to these array data generated spatial auto-correlation coefficients for all the frequency interested. The coefficients from all the data set are averaged to determine the final coefficients. And then the dispersion curves are derived. For SASW, Given the array separation, the phase of the cross power spectrum is used to calculate the relation between Rayleigh-wavelength and frequency, and the wavelength and frequency are, in turn, used to compute the dispersion curve.

It is more direct to look at the measured dispersion curves from both methods to better understand the differences of the two methods than compare the inversed shear wave velocity profiles. So first the dispersion curves from the two methods are compared first. There are 3 sites at which we didn’t get good records, so at totally 23 sites Dispersion curves are analyzed. Dispersion curves for 23 sites both from MAM and SASW are shown in Figure 10. The black triangular scatter line is for the result of MAM and the blue hollow square scatter line for the result of SASW.

In comparing the dispersion curves at each of these sites it was observed that the phase velocity values were often quite consistent between the two methods at the overlapping frequency. The dispersion curve from MAM shows much lower surface wave velocities than were measured with SASW testing at the frequency 15 -20 Hz. A second observation concerns the frequency content of the two tests. The microtremor results measure energy at lower frequencies. The frequency measured by the microtremor method at these sites is on the order of 2.5 to15 Hz. In contrast, the SASW method measures frequencies in the range of 8-120 Hz.

VELOCITY STRUCTURE INVERSION AND COMPARISON

After the dispersion curve is calculated from the field data, the shear wave velocity profile can be calculated in the laboratory. This process is named inversion. And it is the final goal of the analysis to
obtain from the dispersion curve the site shear wave velocity profile. So it is also important to look at
the difference of shear wave velocity profile that inversed from the two methods.

There are some S-wave velocity data measured by borehole method near the testing Site Tuozitou. The shear wave velocity profile of Site Tuozitou is inversed from the dispersion curves analyzed by
the two methods for comparison. According to the relationship among frequency, velocity and
wavelength, the wavelengths measured at this site with MAM are on the order of 10 to 120 m. The
shortest wavelength measured with the SASW method at this site is less than 1 m. The longest
wavelength measured with the SASW method at this site is less than 15 m. Therefore, the SASW
method is able to resolve the near-surface shear wave velocity structure at these sites and MAM can
resolve the deep shear wave velocity structure at these sites.

Many different techniques of inversion have been proposed to obtain soil shear wave velocity
structure starting from the dispersion curve. The inversion can be treated as an optimization problem
for searching the minimum of one objective function. Recent improvements in computational
capabilities have made it possible to gain more accurate solutions. The genetic algorithm is one of the
most powerful global optimization methods. Here the algorithm that combine (GA) and Simplex
Algorithm is applied to invert the soil shear-wave velocity structure from surface-wave dispersion
curve. The form of the objective function used is as equation 8.
Here, $q_o(i)$ and $q_o(i)$ are respectively the dispersion curve derived from microtremors and from numerical modeling. The unknown parameters are four for each layer, i.e. shear wave velocity, thickness, density, and P-wave velocity or Poisson ratio. It is difficult to invert all the soil parameter at one time. We and some other researches have made some studies about the influence of each one of these parameters and the general conclusion is that the influence of density and P-wave velocity is negligible. So they can be estimated on the basis of experience without sensible effects on the final results. Also there exists some trade-off between S-wave velocity and thickness of each layer, i.e. more than one pair of layers thickness and soil stiffness configuration can correspond to the same dispersion curve. So only the simplest case is considered here. Density of each layer is pre-assumed and P-wave velocity is connected to S-wave velocity using the relation $V_p = V_s \sqrt{\frac{3(1-\nu)}{2\nu}}$. Maybe there are some boreholes on the site and the number of layers and thickness of each layer are known. So only the shear wave velocity of each layer need to be determined. Inversion is the process of calculating the shear wave velocity profile by matching of a theoretical dispersion curve with the measured field dispersion curve. In this process, the theoretical dispersion curve is calculated for an assumed velocity profile using the reflection/transmission coefficients approach developed by Kennett and Kerry (1981).
The comparison of shear wave velocity profiles determined from SASW testing and profiles determined from microtremors are shown in Figures 11. The result shows that from SASW we can get fairly good estimation of shallower S-wave velocity structure. Although for this difficult site under which two very thin and soft soils exist, we can get preliminary estimation of deeper S-wave velocity structure from MAM. In order to inverse more complete site S-wave velocity structure both including shallower and deeper information, we also combined and average the dispersion curves from both methods for inversion. The result show much improvement can be obtained for the shallower structures by combining the dispersion curves. But whether there are some improvement for the deeper structures can not be seeing clearly by this comparison. So, further the corresponding site responses spectral under the input of artificial ground motion are computed by the S–wave velocity structures from Borehole method, MAM and combined dispersion curve. The comparison of site responses spectral is shown in Figure 12. The comparison further indicates that MAM can give a preliminary estimation of site dynamic character and combined the result of MAM and SASW will give a better estimation of site dynamic character. And we can conclude that the high frequency components of microtremors should be paid more attention to. More powerful test and analysis methods should be studied to improve the precision of MAM for high frequency components.

CONCLUSION

MAM and SASW are two kind of non-intrusive method for estimating S-wave velocity structure. Both of them based on the dispersion property of Rayleigh wave, there is no systematical difference observed between the dispersion curves from the two methods at 23 different sites. The only difference is MAM results measure energy at lower frequencies whereas the SASW method measures energy at higher frequency.

By comparison of the inverted S-wave velocity with that measured by borehole method at one test site, the results show MAM and SASW method can estimating site dynamic property well. And by combining the two methods better results can be reached. It indicates that the high frequency components of microtremors should be paid more attention to. More powerful observation and analysis methods should be studied to improve the precision of MAM for high frequency components.
Although improvement need be made in some aspect for MAM, it's a promising method for estimating site S-wave wave velocity structures.

ACKNOWLEDGEMENT

This research is sponsored by the National Nature Science Foundation under Grant No.50378032 and Joint Earthquake Science Foundation under Grant No.604034.

REFERENCES


TAO Xiaxin, Robert Kayen, SHI Lijing, SHI Hailiang. (2004), China-Us Joint Surface Wave Investigation. 3th ICCE

