A NEW PROCEDURE
FOR ESTIMATION OF SHEAR WAVE VELOCITY PROFILES
USING MULTI STATION SPECTRAL ANALYSIS OF SURFACE WAVES,
REGRESSION LINE SLOPE, AND GENETIC ALGORITHM METHODS

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Chapter Five

5 Equipment and Software Used to Acquire Experimental Data

This research is another approach to the application of MSASW. The principal purpose of this work is to find shear wave velocity profiles by using the dispersion properties of Rayleigh waves. To achieve the experimental goals of this study, a new system of hardware and software packages have been designed and developed. The system uses electric and electronic equipment controlled by computer codes written in several programming environments. The equipment used in this study is state-of-the-art equipments available in the United States. However, the system of components developed for the experimental part of this study is unique.

This chapter contains a description of the experimental aspect of the study and details of the hardware and software packages used.

5.1 Wave Generation

Generally, there are two categories of sources for generating Rayleigh waves: active and passive sources. In the active category, there are two types of sources: impulsive, where a sledge hammer is used to create waves; and continuous, in which a shaker is used to create harmonic waves. There are advantages and disadvantages to each active and passive source categories. Advantages of active sources are repeatability and control of the source. The latter will make the measurement and analysis of the waves less complex than passive sources. The main advantage of passive sources is providing the ability of measurement and analysis of deeper soils. However, the generated frequencies are unique for each test.

The use of impulsive wave sources will provide a wide range of frequencies simultaneously. Using a continuous harmonic source will provide specific range of
frequencies which are repeatable. Hence, the local external noise will be less effective. This makes these sources more popular to use in soil characterization.

In this study, a continuous harmonic source has been employed. To generate the waveforms, a digital 15 MHz Function/Arbitrary Waveform Generator, model 33120A, manufactured by Agilent Technologies has been used (see Figure 5-1).

![Function/Arbitrary Wave Generator Model 33120A and the controlling computer](image)

This wave generator is controlled by a computer program developed in the VEE PRO platform (see Figure 5-2) via an USB/GPIB interface. A Dual-Mode Power
Amplifier, Model 144, manufactured by APS Dynamics incorporation, amplifies signals generated by the waveform generator.

The amplified signals provide drive power for the vertical reciprocating movements of an APS Model 400 ELECTRO-SEIS Shaker (see Figure 5-3). The shaker is a long stroke, electrodynamic shaker, designed to be used alone or in arrays for exciting and investigating the dynamic response characteristics of structures and soils.
Figure 5-3   APS Model 400 vertical shaker.
The number of frequencies to be measured and the distribution of the frequencies depend on the amount of data that can be practically collected and analyzed, and the dispersive nature of Rayleigh waves (Hebeler, 2001).

In this study, the range of frequencies \((f)\) and the frequency increments \((\Delta f)\) are as follows: (1) \(f = 3.75 \text{ Hz to } 15 \text{ Hz with } \Delta f = 0.625 \text{ Hz};\) (2) \(f = 16.25 \text{ Hz to } 35 \text{ Hz with } \Delta f = 1.25 \text{ Hz};\) and (3) \(f = 37.5 \text{ Hz to } 100 \text{ Hz with } \Delta f = 2.5 \text{ Hz}.

### 5.2 Response Measurement

Surface waves can be detected using sensors installed on the surface of the media (soil). In traditional two-receiver SASW techniques, the two receivers (sensors) are arranged in two different geometries (Nazarian and Stokoe, 1986); this is not the method that has been used in this study. In multi-receiver SASW technique, on the other hand, the receivers could be arranged in a straight line configured by array analysis. In most of the recent studies, the linear array technique has been used (Tokimatsu, 1995; Park et al. 1999; Zywicki 1999; Foti, 2000; and Hebeler, 2001). The use of array analysis has the advantage of eliminating some of the drawbacks of the traditional surface wave testing including, no multiple mode resolution, poor attenuation estimates, low ambient noise tolerance, and time intensive experimental procedures (Hebeler, 2001).

The active sensor array geometry used in this study has been developed by using a smoothing kernel, or array smoothing function (ASF), which equals the Fourier transform of the weighted sensor array (Zywicki, 1999) as

\[
A_S(k) = \sum_{i=1}^{S} w_i \exp\left( j k \cdot x_i \right)
\]

where \(A_S\) is the array smoothing function, \(S\) is the number of sensors in the array; \(w_i\) and \(x_i\) are the weights and the spatial lag of the \(i^{\text{th}}\) sensor respectively; \(j = \sqrt{-1}\) and \(k\) denotes the wavenumber.

The best array function is the one with no side lobe height over the entire wavenumber spectrum. Nevertheless, in reality there is a finite mainlobe width and a side lobe height. Mainlobe width in an array is related to its minimum wavenumber resolution,
and the side lobe height corresponds to the array’s maximum spatial resolution and to its noise removing factor. To optimize the geometry of an array the height of side lobe together with the width of main lobe must be minimized (Zywicki, 1999). The most important advantage of using linear arrays is the increased number of spatial lags over the traditional method. For example, in a traditional case where four pairs of distances from the source are used, the number of different spatial lags would be four. On the other hand, in a multi-sensor case where the sensor arrangement is based on the linear array, the number of different spatial lags $L_s$ and subsequently the number of unique phase records can be obtained from

$$L_s = \sum_{i=1}^{M} (i-1)$$

where $M$ is the number of sensors. Therefore, for a case where 15 sensors are used in an array, the number of unique spatial lags or unique phase angles would be 105.

The locations of 15 sensors obtained using ASF is shown in Table 5-1. Figure 5-4, shows the position of the shaker and receivers based on active array analysis. This is a spacing geometry for 15 receivers placed in a straight line on the ground (Rix et al., 2002).

<table>
<thead>
<tr>
<th>Sensor</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to Shaker (ft)</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>22</td>
<td>28</td>
<td>34</td>
<td>42</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>95</td>
<td>110</td>
</tr>
</tbody>
</table>
Figure 5-4  The test geometry for 15 seismic receivers and one source-mounted receiver.

The present study exploits 12 Wilcoxon Research model 731A seismic accelerometers (see Figure 5-5) featuring:

- Ultra high sensitivity,
- Ultra low-noise electronics for clear signals at sub micro-g levels,
- Low frequency capable,
- Low pass filtered to eliminate high frequencies,
- ESD protection, and
- Miswiring protection

Unlike geophones that generate their own electricity, accelerometers have power boxes that provide required power by batteries. Accelerometers do not need leveling and can be used in any directions while geophones have to be leveled, and are normally used for just up and down movements. The attachment of accelerometers (receivers) to the ground is an important factor of recording accuracy. To achieve a better coupling between soil and accelerometers, special spikes have been designed and fabricated for this study
(see Figure 5-5). At a test site, spikes are inserted in soil and the accelerometers threaded to them, providing very good coupling of accelerometers to the soil.

![Seismic accelerometer installed on a fabricated spike.](image)

**Figure 5-5**  A seismic accelerometer installed on a fabricated spike.

Near field is an important parameter in the sensor arrangement; it is the distance from the source where the body wave field is not negligible. Numerical studies of wave propagation in vertically heterogeneous media show that in normally dispersive media near-field effects are important up to a distance from the source equal to \( \frac{\lambda}{2} \), where \( \lambda = \lambda(\omega) \) is the wavelength of Rayleigh waves as a function of \( \omega \) or the propagation frequency (Holzlohn, 1980; Vrettos, 1991; Tokimatsu, 1995). In inversely dispersive media (see Figure 3-6), that is the media where the properties of material vary irregularly with depth, near-field effects are larger and could be reached up to \( 2\lambda \). Therefore, when designing the sensor arrangement the closest sensor to the source (in our case the shaker) should be placed at a distance equal to one to two times of the smallest wavelength.
5.3 Recording Signals

Most systems used to record signals from accelerometers in surface waves analysis are spectrum analyzers and seismographs. A spectrum analyzer receives amplified and digitized signals and save them in a time domain. Then, the data in time-amplitude space are transferred into the frequency-amplitude space. Using these spectral data, the phase difference and eventually the shear-wave velocity profiles are estimated. A major advantage of spectrum analyzers is the ability to provide on-site dispersion data. Seismographs are multi-channel digital recorders that typically have the ability to record 16 channels of data simultaneously. Just as with spectrum analyzers, the collected data are in time-amplitude space and are transferred into spectral data. Using seismographs does not have the advantage of having on-site dispersion data but provides a lower cost spectral analysis system than spectral analyzers.

In this study, a new low-cost method has been developed. A laptop computer is used to receive and save the time series data from each accelerometer. The interface between the accelerometers and the laptop is a DT9800 USB (universal serial bus) Data Acquisition Function Module manufactured by the Data Translation Company (see Figure 5-6). The filtered and gained signals from each accelerometer’s power box enter the data acquisition module in analog form and exit in a digitized form.
The USB connection in this data acquisition module (DAM) provides a low cost, easy to operate, and a user friendly data acquisition device. The DAM resides outside of the computer and connects to it via a single cable; it supports 16 single-ended or pseudo-differential analog input channels or eight differential analog input channels. Each accelerometer connects to two specific terminals on DAM via a coaxial cable. A program written in the VEE PRO platform (see Figure 5-7) controls the DAM and receives and saves signals in specific files in the computer memory.
The program has a plot area which displays the received time history data from all accelerometers in order to check and compare the quality of received data, and observe the dispersion property of received signals on site (see Figure 5-8). Other plot areas can be added conveniently to the program; a useful plot area is the transformed frequency domain data.
Figure 5-8 VEE PRO DAM program plot area for an on-site display of time domain data from all receivers.

The channels connected to the DAM are configured via a configuration window on A/D configuration object (see Figure 5-9). The configuration window lets the operator change settings and adjustments to DAM, including adding or deleting channels, adding gain to the signals, and changing the sampling rate for each experiment.
To choose the sampling rate, two major factors need to be considered: one, is the nature of Rayleigh waves; and two, is the number of points used in the spectral calculations. The dispersive propagation of Rayleigh waves necessitates obtaining samples at smaller frequency intervals as frequency decreases (Hebeler, 2001). However, due to the practical limitations changing the sampling rate for each frequency during the test is impossible.

In this study, by checking the resolution of several test results and considering the capabilities of the in-hand DAM, a sampling rate of 512 Hz was chosen. For each frequency, the total number of points will be 4,096 which corresponds to 8 seconds of the test time. According to the Nyquist frequency theory, the sampling rate must be at least two times of the maximum test frequency to prevent aliasing. In this study, the sampling rate of 512 Hz is 5 times that of the largest test frequency which is around 100 Hz.