NEW METHODS FOR ENGINEERING SITE CHARACTERIZATION USING REFLECTION AND SURFACE WAVE SEISMIC SURVEYS

by

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ABSTRACT

New Methods for Engineering Site Characterization using Reflection and Surface Wave Seismic Surveys

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This study presents two new seismic testing methods for engineering application, a new shallow seismic reflection method and Time Filtered Analysis of Surface Waves (TFASW). Both methods are described in this dissertation.

The new shallow seismic reflection was developed to measure reflection at a single point using two to four receivers, assuming homogeneous, horizontal layering. It uses one or more shakers driven by a swept sine function as a source, and the cross-correlation technique to identify wave arrivals. The phase difference between the source forcing function and the ground motion due to the dynamic response of the shaker–ground interface was corrected by using a reference geophone. Attenuated high frequency energy was also recovered using the whitening in frequency domain. The new shallow seismic reflection testing was performed at the crest of Porcupine Dam in Paradise, Utah. The testing used two horizontal Vibroseis sources and four receivers for spacings between 6 and 300 ft. Unfortunately, the results showed no clear evidence of
the reflectors despite correction of the magnitude and phase of the signals. However, an improvement in the shape of the cross-correlations was noticed after the corrections. The results showed distinct primary lobes in the corrected cross-correlated signals up to 150 ft offset. More consistent maximum peaks were observed in the corrected waveforms.

TFASW is a new surface (Rayleigh) wave method to determine the shear wave velocity profile at a site. It is a time domain method as opposed to the Spectral Analysis of Surface Waves (SASW) method, which is a frequency domain method. This method uses digital filtering to optimize bandwidth used to determine the dispersion curve. Results from testings at three different sites in Utah indicated good agreement with the dispersion curves measured using both TFASW and SASW methods. The advantage of TFASW method is that the dispersion curves had less scatter at long wavelengths as a result from wider bandwidth used in those tests.
This study presents two new seismic testing methods for engineering application, a new shallow seismic reflection method and Time Filtered Analysis of Surface Waves (TFASW). Both methods are described in this dissertation.

The new shallow seismic reflection was developed to measure reflections at a single point using 2-4 receivers, assuming homogeneous, horizontal layering. Two problems commonly encountered in reflection testing are dealt with in this new method. These problems are: phase shifts between the wave source and ground motion; and, loss of high frequency energy. Using approaches to mitigate these problems significantly improved the shape of measured waveforms. However, none of the sites investigated yielded strong enough reflectors to fully characterize the sites.

TFASW is a new surface (Rayleigh) wave method to determine the shear wave velocity profile at soil and rock sites. The method is an improvement over other surface wave seismic methods because digital filters with optimized bandwidths are used to
characterize the surface wave dispersion. Successful applications of the TFASW method are shown at three sites.
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<td>4.55</td>
<td>Dispersion curves from Array #2, Dannon Factory, West Jordan, Utah</td>
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CHAPTER 1

INTRODUCTION AND OBJECTIVES

1.1 Introduction

Understanding of the properties of soil and rock underlying a site is necessary and important in geotechnical engineering. Many techniques have been used to characterize the material beneath the ground surface. Each technique has both advantages and disadvantages. Drilling and sampling, for example, is a very common and popular method because it can provide sample of soil from the site. However, the disadvantages of drilling and sampling are that it disturbs the site, has high costs, and it is inappropriate for large areas. One alternative method is using geophysics to determine engineering properties of soil and rock underlying a site.

A seismic reflection survey is one geophysical method that uses seismic waves to determine the stiffness and thickness of soil layers based upon the velocity of seismic waves propagating through the materials. Major advantages of the reflection test are that it does not require a borehole, so the site is not disturbed, and testing is relatively quick, easy and inexpensive. Seismic reflection is the method of choice for deep profiling for oil exploration. However, there are many challenges in applying the method to shallow profiling for engineering investigations. Reflections off of shallow impedance contrasts are often obscured by larger magnitude surface waves. Shallow reflections require higher frequency waves than deep profiling. These high frequency waves are subject to large attenuation in soft soil, and there are higher levels of environmental noise at these higher frequencies. Recent reflection surveys use the Vibroseis as sources because the frequency content is uniform (white) over a selected frequency band, and it provides
sharp cross-correlations. However, the source forcing function is not in phase with the
motion of the ground due to the dynamic response of the shaker–ground interface.
When receiver signal does not have a consistent phase-shift with the forcing function, the
cross-correlation function does not have a single primary lobe at the wave arrival and side
lobes are large.

This dissertation is going to demonstrate a new shallow seismic reflection method
that uses fewer geophones. Unlike the conventional reflection surveys that use a large
number of geophones, this testing uses only two to four geophones in the field
configuration. Several signal processing techniques are employed to deal with the
problems mentioned earlier. Whitening in the frequency domain is used to compensate
loss of energy at high frequencies. The using of a reference geophone is used to correct
the difference between the source function and the ground motion.

Surface waves analysis is another way to explore subsurface materials. Unlike in
reflection testing, most of the energy generated from a surface excitation propagates as
surface waves. Surface wave methods, like reflection methods, do not require expensive
boreholes, and evaluate undisturbed material properties.

There are two common surface wave methods, Spectral Analysis of Surface
Waves (SASW) and Multichannel Analysis of Surface Waves (MASW). SASW is a
simple test that uses only 2 to 4 receivers and a simple Fourier transform for spectral
analysis. However, the Fourier analysis uses uniform frequency bandwidth leading to
narrow bandwidths at low frequencies that leads to poor resolution of low frequency
waves required for characterizing deeper layers.
MASW is another test using many receivers to control bandwidth in spectral analysis and characterize different modes of surface waves. The problem of MASW is it requires many sensors which make it a complicating field testing.

This research will demonstrate a new method called the Time-Filtered Analysis of Surface Wave (TFASW). It is a method that uses two to four receivers, similar to the SASW method. However, the TFASW uses digital filtering that allows to select bandwidth to determine dispersion curve and the data are recorded and stored in the time domain instead of the frequency domain for SASW. By using wider bands, the signal-to-noise ratio is improved leading to better resolution of low frequency waves.

1.2 Objectives

The focus of this research was to develop testing, signal processing and analysis methods to improve both reflection and surface wave surveys.

1.2.1 Objectives of a New Shallow Reflection Method for Engineering Applications

There are 6 objectives for a new shallow reflection method for engineering applications. These are: 1) to develop a method to measure reflection at a single point using 2-4 receivers, assuming homogeneous, horizontal layering, 2) to use one or more shaker driven by a swept sine function as a source, 3) to identify wave arrivals using cross-correlation, 4) to improve cross-correlations using phase corrections. The reference geophone is used in this research to correct the phase difference between the source forcing function and the ground motion, 5) to recover attenuated high frequency energy using whitening technique. The energy of the signal is going to be balanced (whitened) throughout the frequencies. Narrower side lobes are expected in the crosscorrelation due
to the recovery of high frequency waves, and 6) to clean noise from data in time-
frequency domain.

1.2.2 Objectives of the Time Filtered Analysis of Surface Waves (TFASW)

The objective of this research was to develop a new surface wave method called Time Filtered Analysis of Surface Waves (TFASW). The purpose of creating this method was to improve the resolution of low frequency waves by using more ideal bandwidth. Better energy distribution and higher signal-to-noise ratio at low frequencies are observed as a result of wider bandwidth.

1.3 Outline of Dissertation

Chapter 2 represents a literatures review. The content is divided into three different sections: the basic seismic wave properties, the seismic reflection surveys and the surface wave analyses.

Chapter 3 presents testing procedure, signal processing and methods of analysis of the seismic reflection survey with fewer geophones. The techniques of the whitening in frequency domain, the Gabor spectrum filter and the using of a reference geophone are discussed. The results of the field experiment are also demonstrated in this chapter.

Chapter 4 introduces a new surface wave analysis called Time Filtered Analysis of Surface Waves (TFASW). The procedure and analysis methods of the testing are demonstrated. The field experiments and comparisons between the new method and the Spectral Analysis of Surface Waves (SASW) are presented in the chapter as well.

Chapter 5 contains the summaries and the conclusions of this dissertation. Recommendations for further study are also included in the chapter.
CHAPTER 2
LITERATURE REVIEW

This chapter reviews the literature on three different topics. The first topic is basic properties of seismic waves. The second topic is seismic reflection surveys. The third topic is seismic survey methods using surface waves including the Spectral Analysis of Surface Waves (SASW) and the Multichannel Analysis of Surface Waves (MASW). It describes the applications of both techniques and compares the advantages and disadvantages of these two methods.

2.1 Basic Properties of Seismic Waves

Seismic waves occur when a particle is displaced and elastic forces cause the particle to rebound relative to adjacent particles. For example when a ground is hit by a hammer, the ground surface is disturbed by that hammer and causes the wave to propagate outward from the point where the hammer impacts the ground surface. This section describes basic properties of seismic waves. The topics are: types of seismic waves, sinusoidal motion analysis in time and frequency domains, Fourier transforms, Gabor transforms, correlation techniques, and wave propagation.

2.1.1 Types of Seismic Waves

Seismic waves can be separated into two types, body waves and surface waves. Body waves can be divided into two categories, primary waves and secondary waves. Primary waves, also called P-waves, are the longitudinal waves that cause particle displacement in the same direction that the waves propagate. This causes compression when the particle velocity is in the same direction as the wave propagation velocity, and
in tension when the particle velocity is in the direction opposite to wave velocity. The second type of body wave is secondary waves, also called S-waves or shear waves. Shear waves are the waves that generate particle displacements perpendicular to the direction of wave propagation. Shear waves also can be divided into vertical shear (SV) and horizontal shear (SH) waves indicating the displacement director. Fig. 2.1 shows the particle motions of planar body waves where the initial condition, the motion of P-waves, and the motion of S-waves are represented in Fig. 2.1 (a), (b), and (c), respectively. Fig. 2.2 presents the wavefronts and raypaths of body waves when they propagate over a period of time from a point source.

Fig. 2.1 P-wave and S-wave particle motion from Santamarina (2001)
The other type of seismic waves is surface waves. Surface waves can also be separated into two categories, Rayleigh waves and Love waves. Rayleigh waves travel along the ground surface and the particles move as ellipses in both vertical and parallel to the direction of the wave propagation. Love waves are basically horizontal shear waves that propagate along the surface. The particle motions of both Rayleigh waves and Love waves are shown in Fig. 2.3.
2.1.2 Sinusoidal Motion

Sinusoidal motion can be represented using both trigonometric and complex notations. Important features of a wave are amplitude, frequency, and phase. Amplitude, $A$, indicates the size of the peak of the wave. Frequency, $f$, is the inverse period of the wave with units of cycles per second, or Hertz (Hz). Phase, $\phi$, is the parameter that represents a shift of the wave from a pure sine function. Characteristics of a sinusoidal wave are shown in Fig. 2.4.

Mathematical expressions for a sinusoid are:

\[
\begin{align*}
\text{Trigonometric:} & \quad u(t) = A\sin(\omega t + \phi), \\
\text{Complex:} & \quad u(t) = \frac{A}{2}e^{i(\omega t + \phi)} + \frac{A}{2}e^{-i(\omega t + \phi)},
\end{align*}
\]

where $A = \text{amplitude} = \sqrt{a^2 + b^2}$,

$\omega = \text{circular frequency} = 2\pi f$,

$t = \text{time}$,

$f = \text{frequency}$,

$\phi = \text{phase angle} = \tan^{-1}\left(\frac{b}{a}\right)$, and

$i = \sqrt{-1}$.

2.1.3 Time and Frequency Domains

Time domain is the simplest way to observe a signal representing particle motion of a wave. Data in time domain are all real numbers, particle displacement, velocity or acceleration. Seismographs are typically used for recording the seismic waves in time domain.
Similarly to time domain, frequency domain is a representation of a signal versus frequency. The data in frequency domain are complex numbers. These complex numbers in the frequency domain, called spectrum, contain information about magnitude and phase of the signal. The magnitude tells how much energy in different frequency and the phase tell the lag or time-shift of the signal.

2.1.4 Fourier Transforms

The Fourier transform is a mathematical operation that is applied to transform data from the time domain to the frequency domain. The forward Fourier transform is (Proakis and Manolakis 2004):

$$X(F) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft} dt,$$  \hspace{1cm} 2.3

and the reverse Fourier transform is:
\[ x(t) = \int_{-\infty}^{+\infty} X(F) e^{i2\pi ft} dF, \]

where \( x(t) = \text{signal in time domain}, \)

\( X(F) = \text{signal in frequency domain}, \)

\( i = \sqrt{-1}. \)

The forward transform goes from time domain to frequency domain, while the reverse transform goes from the frequency domain to time domain.

### 2.1.5 Gabor Transforms

Gabor transform is another mathematical transform used to transform data to the time-frequency domain. In the time-frequency domain, one can evaluate how the frequency content of a signal changes with time. The Gabor transform is applied by multiplying the time domain signal by a succession of Gabor analysis windows, usually a Gaussian function. The windowed time signals are then transformed into the frequency domain using a Fourier transform. After performing a Gabor transform, the result represents time-frequency relationship of the original function. The equation for the forward Gabor transform is (Wang 2006):

\[ U(\tau, \omega) = \int_{-\infty}^{\infty} u(t)w(t - \tau) \exp[-i\omega t] \, dt, \]

where \( U(\tau, \omega) = \text{signal in Gabor domain}, \)

\( u(t) = \text{signal in time domain}, \)

\( w(t) = \text{Gabor analysis window}, \)

\( \tau = \text{center of the window}. \)

The inverse Gabor transform is:
where \( h(t) = \) the Gabor synthesis window = \( \left[ \int_{-\infty}^{\infty} w(t - \tau) d\tau \right]^{-1} \).

Forward and reverse Gabor transforms on a signal will exactly replicate the original signal.

2.1.6 Correlations

Cross-correlation is a mathematical procedure used to measure the similarity between two different signals as a function of time lag. It is the sum of the product of the two signals with one of the signals shifted in time. Values of cross-correlation are greater at time shifts where the two signals are more similar and lower at time shifts where the signals are less similar. The cross-correlation of two signals, \( x(t) \) and \( y(t) \), is defined as (Proakis and Manolakis 2004):

\[
 r_{xy}(l) = \sum_{n=-\infty}^{\infty} x(n + l) y(n),
\]

where
\( x(n) = \) time domain signal one,
\( y(n) = \) time domain signal two,
\( n = \) number of point, and
\( l = \) time shift parameter =0, ±1, ±2,…

Another correlation technique is the auto correlation. Auto-correlation is the cross-correlation of a signal with itself. Auto-correlation always shows a maximum value at a time-shift of zero. Auto-correlation is:
\[ r_{xx}(l) = \sum_{n=-\infty}^{\infty} x(n + l)x(n). \] 2.8

### 2.1.7 Wave Propagation

One dimensional wave propagation equation can be derived from wave motion in a rod. In this section two different types of motion, longitudinal and torsional, are derived (Richart et al. 1970).

For longitudinal wave propagation, free vibration of a rod with uniform stress is considered as shown in a free body diagram, Fig. 2.5. Properties of the rod are cross-sectional area, \( A \), Young’s modulus, \( E \), and unit weight, \( \gamma \). Based on the free body diagram, a summation of forces in x-direction is:

\[-\sigma_x A + \sigma_x A + \frac{\partial \sigma_x}{\partial x} \Delta x A = F.\] 2.9

Then, applying Newton’s second law to relate the force and displacement, \( u \):

\[-\sigma_x A + \sigma_x A + \frac{\partial \sigma_x}{\partial x} \Delta x A = \Delta x A \frac{\gamma}{g} \frac{\partial^2 u}{\partial t^2},\] 2.10

\[\frac{\partial \sigma_x}{\partial x} = \frac{\gamma}{g} \frac{\partial^2 u}{\partial t^2}.\] 2.11

By applying Hooke’s law:

\[\frac{\partial \sigma_x}{\partial x} = E \frac{\partial^2 u}{\partial x^2}.\] 2.12

From Equation 2.11 and Equation 2.12, and mass density \( \rho = \gamma/g \):

\[E \frac{\partial^2 u}{\partial x^2} = \rho \frac{\partial^2 u}{\partial t^2}.\] 2.13
Finally, the longitudinal wave equation is written as:
\[
\frac{\partial^2 u}{\partial x^2} = v_c^2 \frac{\partial^2 u}{\partial t^2} \tag{2.14}
\]
where \( v_c = \sqrt{E/\rho} \).

This wave equation describes longitudinal waves in a rod with free boundaries. P-waves are described by:
\[
\frac{\partial^2 u}{\partial x^2} = v_p^2 \frac{\partial^2 u}{\partial t^2}, \tag{2.15}
\]
where \( v_p = \sqrt{M/\rho} \), and
\[
M = \text{constrained modulus} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}. \tag{2.16}
\]

Similar to the longitudinal waves, the wave equation for torsional waves can be derived using a dynamic equilibrium and shear modulus of a rod. In this case, element is rotated due to the torques rather than displaced from normal forces. A free body diagram of the element is shown in Fig. 2.6 where \( T \) is torque, \( \theta \) is angle of rotation, \( I_p \) is polar moment of inertia, and \( \Delta x \) is the length of the element. Applying the Newton’s second law gives:
\[
-T + \left( T + \frac{\partial T}{\partial x} \Delta x \right) = \rho I_p \Delta x \frac{\partial^2 \theta}{\partial t^2}, \tag{2.16}
\]
or,
\[
\frac{\partial T}{\partial x} = \rho l_p \frac{\partial^2 \theta}{\partial t^2}.
\]

Because \( T = G I_p \frac{\partial \theta}{\partial x} \) where \( G \) is shear modulus, Equation 2.17 becomes:

\[
\frac{\partial}{\partial x} \left( G I_p \frac{\partial \theta}{\partial x} \right) = \rho I_p \frac{\partial^2 \theta}{\partial t^2}.
\]

The above equation can be rewritten as the wave equation of torsional waves as follows:

\[
\frac{\partial^2 \theta}{\partial t^2} = v_s^2 \frac{\partial^2 \theta}{\partial x^2},
\]

where \( v_s = \sqrt{G/\rho} \),

\( G \) = shear modulus, and

\( \frac{\partial \theta}{\partial x} \) = angle of twist per unit length.

Three dimensional wave propagation equations can also be derived from a homogeneous, isotropic, infinite elastic, material, as seen in Fig. 2.7, by using a dynamic equilibrium (the second law of Newton), and properties of material. The wave equations of P-wave and S-wave of an infinite elastic material are:

\[
\frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = v_p^2 \nabla^2 \bar{\varepsilon},
\]

where \( \bar{\varepsilon} \) = dilatation,

\( v_p = \sqrt{(\lambda + 2G)/\rho} \), and

\[
\frac{\partial^2 \vec{\omega}_x}{\partial t^2} = v_s^2 \nabla^2 \vec{\omega}_x,
\]

where \( \vec{\omega}_x \) = rotation in x direction, and

\( v_s = \sqrt{G/\rho} \).

Similar equations can be found for y and z directions.
2.2 Seismic Reflection Surveys

A seismic reflection survey is one geophysical method that uses seismic waves to determine the stiffness and thickness of soil layers based upon the velocity of seismic waves propagating through the materials. The seismic reflection survey has been used in the petroleum industry for over 70 years and in shallow applications since 1980 (Steeples and Miller 1990). Many techniques and instruments such as dynamites and mobile sources, have been developed. A brief history of sources used in seismic exploration was discussed by Bay (1997). The source discussed in this section is the Vibroseis which is a
mechanism that generates a controlled sweep signal into the ground. This section also discusses whitening and Q-filtering techniques which were created to improve the resolution of seismic reflection surveys.

There are two types of body waves that have been used in seismic reflection surveys, compression waves (P-waves) and shear waves (S-waves). Vertical and horizontal geophones are used for P-waves and S-waves, respectively. The advantages of using shear waves instead of compression waves are that shear waves are not affected by the pore fluid in the soil and shear waves propagate better than compression waves in dry and loose soil (Pullan et al. 1990).

2.2.1 Conventional Seismic Reflection Test

The seismic reflection test is a geophysical method that can be used to find wave velocity versus depth in subsurface soil and rock. The reflection test analysis is based on three basic assumptions (Kramer 1996): 1) subsurface layers are homogenous; 2) subsurface layers are isotropic; 3) seismic wave ray paths are straight within a layer.

This method starts by generating waves from the source, at the ground surface, and allows them to propagate through the soil beneath and reflect back from the soil layer boundaries to the receivers. Simple wave propagation in a two layer system using a seismic reflection test with common centerline is indicated in Fig. 2.8, where $S$ is a source location, $R$ is a receiver, $x$ is a distance between the source and the receivers, $H$ is layer depth, and $V$ is wave velocity.

Travel time of a reflected wave can be measured as the time required for the wave to travel downward to hit the soil layer boundaries and reflect back to the receivers. The
relationship between travel time, $t_r$, and source receiver offset, $x_i$, can be described via

Green’s equation (Burger et al. 2006) as:

$$t_r = \frac{\sqrt{4H_{total}^2 + x^2}}{v_{avg}},$$

where $H_{total} = \text{total depth}$,

$x = \text{distance between source and receiver}$, and

$v_{avg} = \text{average velocity of reflected wave}$ is:

$$v_{avg} = \frac{H_1 + H_2 + \cdots + H_n}{\frac{V_1}{V_1} + \frac{H_2}{V_2} + \cdots + \frac{H_n}{V_n}}.$$

By fitting the hyperbolic function in Equation 2.22 to measured reflection arrival times at various offsets as shown in Fig. 2.9, thickness of the soil layer, $H$, can be computed using:

$$H = 0.5 \sqrt{t_{r_0}^2 v_{avg}^2 - x^2}.$$

Fig. 2.8 Seismic reflection survey with common center line
2.2.2 The Vibroseis Method

A brief history of the Vibroseis method was summarized by Bay (1997). The Vibroseis method was developed from the technology of radar and sonar research. The focus of the method is to increase the energy of propagating waves by increasing the driven time rather than increasing the source power. A chirp, sweep, signal was used because it has no repetitive part and it can be transformed into a pulse using cross-correlation technique. In 1952, the Continental Oil Company (Conoco) developed the Vibroseis truck to transfer chirp signals into the ground. The data are recorded by the receivers (geophones) and subsequently converted to be an impulse signal by cross-correlation in order to find reflections from sub-surface layering. The signal is generated by a vibrator that can generate energy over a range of frequencies. Advantages of Vibroseis method are that boreholes for explosives are not required, the frequency
spectrum is controllable, sources can be stacked to increase the signal-to-noise ratio, and it requires less time and cost than dynamite blasting.

Braile (2007) explained the mathematical Vibroseis correlation by using a synthetic Vibroseis sweep signal. The study described the cross-correlation of the Vibroseis source with the measured signal calculated in frequency domain. The cross-correlation in frequency domain is written as:

$$S(f) = Amp[SW(f)]^2 \cdot Amp[E(f)] \cdot e^{i(Phase[E(f)])}$$

where $S(f)$ = cross-correlation,

$Amp[SW(f)]$ = amplitude of source,

$Amp[E(f)]$ = amplitude of earth response,

$Phase[E(f)]$ = phase of earth response, and

\(j = \sqrt{-1}\).

2.2.3 Whitening

Signal whitening is a process used in reflection surveys to equalize the output signal level across the frequency spectrum. It removes the frequency-dependent effect of intrinsic attenuation, and perhaps scattering, making reflections in whitened signals appear sharper and more impulsive than in non-whitened signals.

Cahit and Costain (1983) represented noise attenuation by using Vibroseis whitening (VSW). The Vibroseis whitening works by first doing an auto gain control (whitening) in time records and then doing a correlation. Fig. 2.10 shows the power spectrum of data before and after VSW. The power spectrum of the signal becomes more uniform after doing a whitening. In the case shown in Fig. 2.10, VSW increases the
energy between 50 Hz and 80 Hz. This results in sharper arrivals and less ringing in the cross-correlated signals as shown in Fig. 2.11.

Fig. 2.10 Power spectrum before and after VSW from Cahit and Costain (1983)

Fig. 2.11 Comparison of seismograms before and after VSW from Cahit and Costain (1983)
2.2.4 Inverse Q-filtering

Wang (2006) use a different approach to whiten signals called filtering. Radiation attenuates signals uniformly at all frequencies as they travel from its source. Material damping, however, attenuates high frequencies more than lower frequencies. A stabilized inverse Q-filter amplifies signals inverse proportionally to the attenuation in the ground due to material damping. The equation for inverse Q-filter is:

\[
U(\tau + \Delta \tau, \omega) = U(\tau, \omega) \exp \left[ \frac{(\omega/\omega_h)^{-\gamma}}{2Q_r} \omega \Delta \tau \right] \times \exp \left[ i \left( \frac{\omega}{\omega_h} \right)^{-\gamma} \omega \Delta \tau \right],
\]

where

- \( U \) = plane wave,
- \( \tau \) = traveltime,
- \( \gamma = (\pi Q_r)^{-1} \),
- \( Q_r = Q(\omega) \) at an arbitrary reference frequency,
- \( \omega \) = Angular frequency, and
- \( \omega_h = \) tuning parameter at highest possible frequency = \( 2Q/\tau \).

The first exponential function adjusts the spectral amplitude, and the second the phase-shift. The filter is stabilized to minimize amplification of noise at high frequencies limiting the highest frequency to \( \omega_h = 2Q/\tau \). Gain curves of inverse Q-filtering using stabilized (solid line) and gain-limited (dashed line) methods are shown in Fig. 2.12.

![Fig. 2.12 Gain curve of inverse Q-filtering from Wang (2006)]
2.2.5 Field Applications of the Seismic Reflection Surveys

Many studies of the seismic reflection survey have been performed. Most have been deep imaging for oil exploration. Various sources and techniques have been used based upon the goal of the survey. This section shows some shallow reflection surveys using P-waves or S-waves as these are more applicable for engineering application.

Fowler and Waters (1975) performed P-wave Vibroseis surveys to find crustal reflections in Oklahoma area. The survey used a combination of five Conoco vibrators and one 36,600 lb peak force vibrator using the downsweep frequency range of 20 to 5 Hz and the sweep rate of 0.5 Hz/sec. The receivers were set up as a star pattern which contained 240 total geophones. A total of 7 patterns were used with 880 ft spacing and the maximum offset was 40 miles. The tests provided good signal-to-noise ratio, the results indicated only two clear refractions and unidentified reflections due to complexity of subsurface structure. The time-distance plot of the tests was illustrated in Fig. 2.13 where the dotted lines represented unidentified reflected signals.

Pullan and Hunter (1985) performed analytical model studies and experimental comparisons of P-wave reflection tests on overburden (soil) over bedrock. For analytical modeling, they used three models of two-layer systems to study amplitude and phase behavior at various offsets. The top layer of the models was the overburden with a depth of 30 m, and a compressive wave velocity of 1500 m/s. The second layer was bedrock with velocities of 2500, 3750, and 6000 m/s in the three models. The critical angle was the angle that transmitted waves emerged at 90 degree. In this study, the first and the second critical angles were the critical angle of P-waves and S-wave, respectively. Their
Fig. 2.13 Acquired data plotted in time-distance after Fowler and Waters (1975)

results indicated that if the distance between source and receiver was not larger than the
depth to bedrock, there was no phase change for the reflection, otherwise the phase
changed after the first critical angle for low velocity contrasts and the phase changed after
the second critical angle and created an inversion of 180 degree change in phase for high
velocity contrasts. It also indicated that the amplitude decreased gradually with
increasing offset except that the maximum amplitude can be observed at the first critical
angle, and the second biggest peak can be observed at the second critical angle. There
was a transition zone between the first and the second critical angles which made the
amplitude of the wavelets lower. Characteristic changes of reflections mentioned before
were summarized in Fig. 2.14. Similar behaviors were also measured in field studies.
Pullan et al. (1990) performed shallow reflection surveys at several shallow bedrock sites using shear waves. Their study suggested that quality of the signal mainly depended on the dispersion of surface wave which could mask out most of the reflected signals. Ranges of poor to excellent signal quality were shown in the study. Fig. 2.15 showed poor data where there was significant interference between surface waves and reflected shear waves. In the other hand, Fig. 2.16 shows high quality data from a site with no interference between shear and surface waves.

Baker et al. (1998) improved the quality of near-surface reflection data by muting the noise cone. The data were from a site in southeastern Kansas with the purpose of finding bedrock and investigating subsurface conditions. The source used was 8-gauge surface Besty seisgun and the receivers were 100 Hz geophones. A quarter of a second
of record length was used with the sampling interval of 0.5 msec. Air waves were evident at the receivers, but arrived later than the reflected wave, in what they called the noise cone. The results showed improved data quality by muting the noise cone, as shown in Fig. 2.17. Wave arrivals in the noise cone were surface waves and air blast. Reflections from the bedrock (limestone and shale) and faults were found using this approach.
Harris et al. (2000) successfully mapped the geological structures of the Fraser River delta in British Columbia, Canada using shear wave reflection technique. The tests were performed in three areas with a 135 kg Vibroseis source using swept frequencies from 25 to 150 Hz with an eight seconds record length. Fourteen Hertz geophones and 180 channel seismograph were used to record wave arrivals. The longest offsets were 385, 205, and 280 m for sites one, two, and three, respectively. The seismic reflection sections of the sites were shown in Fig. 2.18. Site one and site two showed reflections at around 1.1 sec and around 0.7 sec, respectively. However, site three could not show clear reflections but it was the first look for the unexplored bedrock. This study demonstrated the ability to observe subsurface geological structures using shear wave reflections.
Fig. 2.18 Seismic reflection sections from Harris et al. (2000)

Inazaki (2006) applied S-wave reflection surveys to delineate shallow subsurface conditions in urban areas of Japan. Surveys were performed at three sites in these studies using a technique called “Land Streamer – textile belts with geophones mounted on top” to speed the testing and to obtain higher quality data. The land streamer was 30 m long and used a 50 cm geophone spacing. Shear waves were generated by striking a wooden plank with 4 kg sledge hammer to create frequencies higher than 100 Hz. Geological structure to a depth of 60 m was explored. The results revealed an undisclosed fault at one site and showed sub-surface structure at the other sites. The depth section interpreted from shear wave reflections at Nagoya Port area, Japan was shown in Fig. 2.19. This study also successfully used shallow S-wave reflection surveys.
Kurahashi and Inazaki (2006) performed a shear wave reflection survey in the southern part of the epicentral area of the 2003 Northern Miyagi earthquake in order to investigate the extent of the fault. The survey was performed using a shear wave vibrator truck as a source with frequencies from 10 to 32 Hz. In total, 144 channels were used with a 10 m interval between geophones. The maximum offset of the furthest receiver was 1,800 m. The acquired data were processed using many techniques such as gain recovery, band-pass filtering, and stacking methods. The results, Fig. 2.20, showed clear reflections from the boundary between two strata at around one second. They found that length of this flexure, shown on the left side of Fig. 2.20, was longer than the initial estimation from aerial-photos.
Polom et al. (2008) explored the subsurface condition in Krueng Aceh River Basin, Sumatra, Indonesia using a shallow shear wave reflection survey. The study was executed using small electro-dynamic shaker as a source to generate an upward sweep signal with frequencies from 10 Hz to 330 Hz over 10 sec. They used 48 channels with a 2 m geophone spacing. They found clear reflectors from depths between 50 and 150 m. An example of a clear reflection that was detected at offset of 0 and 300 ms is shown in Fig. 2.21. The study also classified surface soils from soft soil to very dense soil based on $V_{S30}$.

2.3 Surface Wave Analyses

When a vertical force or impact is applied to the ground surface, approximately 67% of the energy propagates as Rayleigh waves (Richart et al. 1970). Several geophysical tests utilize Rayleigh waves. Two of the most popular surface wave methods are Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves.
Waves (MASW). Unlike downhole and crosshole methods, the SASW method does not require boreholes at the site. Therefore, surface wave methods are nonintrusive, less time consuming, and generally less expensive. With an ability to provide accurate shear wave velocity profile of the subsurface without disturbing the site, both approaches have been widely used since their development. This chapter will provide details about each method, including field and analysis procedures.

2.3.1 Spectral Analysis of Surface Waves (SASW)

Spectral Analysis of Surface Waves, called SASW, is an in-situ geophysical method developed at the University of Texas at Austin to characterize the shear wave velocity profile of subsurface materials (Stokoe et al. 1994). The SASW method is an easy testing that uses only 2 to 4 receivers and a simple Fourier transform for spectral analysis. The basic concept of this method is to calculate the phase velocity between two receivers placed on the ground surface. With a wide range of frequencies generated by a source or sources, a dispersion curve is created and a shear wave velocity profile can be determined using a forward modeling and inversion analysis.

This section discusses three steps of the SASW method. The first is the field procedure. The second is generation of a dispersion curve. And the last is construction of a soil profile using a forward modeling.

2.3.1.1 Field Procedures

Equipment used in the SASW method are a wave source, two receivers, and a spectrum analyzer. The surface waves are created by a source or sources that generated energy over a wide range of frequencies. A low frequency source is required for deeper
profiling and a high frequency source is required to profile near-surface soils. The generated waves are measured using receivers (accelerometers, geophones, or seismometers). The signals from the receivers are recorded using a spectrum analyzer. The spectrum analyzer calculates the energy and phase of each frequency. Wave velocities are calculated at each frequency based upon the phase-shift and receiver spacing.

The configuration of a wave source and two receivers of SASW testing are shown in Fig. 2.22. The distance between the source and the first receiver and the distance between the first receiver and the second receiver is usually the same. Spacings between the source and two receivers also vary with the frequencies of the source waves. Close spacings are used for high frequency waves (shallow profiling) and long spacings are for low frequency waves (deep profiling).

The acquired time domain signals, Fig. 2.23, are transformed into the frequency domain, Fig. 2.24, using a discrete Fourier transform (DFT). The transformations of receiver one and receiver two are:

\[ x(t) \overset{\text{DFT}}{\longrightarrow} X(f), \]

\[ y(t) \overset{\text{DFT}}{\longrightarrow} Y(f), \]

where

\[ x(t) = \text{time domain signal of receiver one}, \]

\[ y(t) = \text{time domain signal of receiver two}, \]

\[ X(f) = \text{frequency domain signal of receiver one}, \]

\[ Y(f) = \text{frequency domain signal of receiver two}. \]
The phase of the cross spectrum and the coherence are (Stokoe et al. 1994):

\[
\phi(f) = \arctan\left( \frac{\text{Im}(G_{XY})}{\text{Re}(G_{XY})} \right), \quad 2.27
\]

\[
\gamma^2 = \frac{G_{XY}G_{XY}^*}{G_{XX}G_{YY}}, \quad 2.28
\]

where \( G_{XX} = X^*(f)X(f) \), \( G_{YY} = Y^*(f)Y(f) \), \( G_{XY} = X^*(f)Y(f) \), and

* = complex conjugate of the quantity.

Phase spectrum expresses the phase difference of two receivers and coherence expresses a normalized measure of the cross-correlation of the data. Averaging is performed using multiple realizations to improve the quality of signals. The higher the coherence (maximum at one) the higher the signal-to-noise ratio is.
After acquiring all data, next step of calculation is to create an experimental dispersion curve, a plot of surface wave phase velocities versus wavelengths/frequencies. Before generating a dispersion curve, poor quality and near-field data have to be masked out as shown in Fig. 2.25. Poor quality data can be observed from either the phase plot or from low coherence. The criterion of near field effect is (Stokoe et al. 1994):

$$\lambda_R < 2d,$$

where $\lambda_R$ = wavelength of Rayleigh wave, and $d$ = spacing between two receivers.
After masking out poor and near field data, wavelength of the signal can be calculated from an unwrapped phase. The expression is:

\[ \lambda_R = d \times \frac{360}{\phi_{21}} \]  

where \( \lambda_R \) = wavelength of Rayleigh wave,
\( d \) = spacing between two receivers, and
\( \phi_{21} \) = phase-shift between two receivers.

After knowing the wavelength, surface wave phase velocity at each frequency is:

\[ v_R = f \times \lambda_R \]  

where \( v_R \) = Rayleigh wave phase velocity, and
\( f \) = frequency.

With broad range of frequencies, a complete dispersion curve can be created as illustrated in Fig. 2.26.
The shear wave velocity profile is generated after creating the experimental dispersion curve. Different profiles would be trialed, conducted by differences in layers depth, Poisson’ Ratio, soil density, S-wave velocity and P-wave velocity, to create theoretical dispersion curve. To be noted that the parameters that affect the dispersion curves the most are the depth and the S-wave velocity, and P-wave velocity always equals to 5000 ft/s for fully saturated soil. The stiffness matrix for layered system can be applied to find the surface wave velocity at different frequency (Kausel and Roesset 1981). The stiffness matrices are:

\[ [P] = [K][U], \]  \hspace{1cm} 2.32

where \([P]\) = external load vector,
\([K]\) = stiffness matrix of the layer,
\([U]\) = displacement vector,
\[
[K] = 2kG \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix}; \text{ for single layer,} \quad 2.33
\]

\[
K_{11} = \frac{1 - s^2}{2D} \begin{bmatrix} \frac{1}{s}(C^r C^s - rs C^s S^r) & -(1 - C^r C^s + rs S^r S^s) \\ -(1 - C^r C^s + rs S^r S^s) & \frac{1}{r} (C^s S^r - rs C^r S^s) \end{bmatrix}
- \frac{1 + s^2}{2} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad 2.34
\]

\[
K_{12} = \frac{1 - s^2}{2D} \begin{bmatrix} \frac{1}{s}(rs S^r - S^s) & -(C^r - C^s) \\ C^r - C^s & \frac{1}{r} (rs S^s - S^r) \end{bmatrix}, \quad 2.35
\]

\[
K_{21} = \frac{1 - s^2}{2D} \begin{bmatrix} \frac{1}{s}(rs S^r - S^s) & C^r - C^s \\ -(C^r - C^s) & \frac{1}{r} (rs S^s - S^r) \end{bmatrix}, \quad 2.36
\]

\[
K_{22} = \frac{1 - s^2}{2D} \begin{bmatrix} \frac{1}{s}(C^r C^s - rs C^s S^r) & -(1 - C^r C^s + rs S^r S^s) \\ -(1 - C^r C^s + rs S^r S^s) & \frac{1}{r} (C^s S^r - rs C^r S^s) \end{bmatrix}
+ \frac{1 + s^2}{2} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad 2.37
\]

\[
[K] = 2kG \begin{bmatrix} 1 - s^2 \\ 1 \end{bmatrix} \begin{bmatrix} r & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}; \text{ for half-space,} \quad 2.38
\]

where

\[
r = \sqrt{1 - \left(\frac{V}{V_p}\right)^2},
\]

\[
s = \sqrt{1 - \left(\frac{V}{V_s}\right)^2},
\]

\[C^r = \cosh krh,\]

\[C^s = \cosh ksh,\]

\[S^r = \sinh krh,\]

\[S^s = \sinh ksh,\]
\[ D = 2(1 - C^r C^s) + \left(\frac{1}{r_s} + r_s\right)S^r S^s, \]

\[ V = V_R = \text{Rayleigh wave phase velocity}, \]

\[ V_S = \text{shear wave velocity}, \]

\[ k = \text{wave number} = \frac{2\pi}{\lambda}, \text{ and} \]

\[ h = \text{layer thickness}. \]

Rayleigh wave velocity at different frequency can be calculated by vanishing the stiffness matrix, setting the determinant of \([K] = 0\). The best fit between experimental and theoretical dispersion curves, shown in Fig. 2.27, provides the most optimum shear wave velocity profile as illustrated in Fig. 2.28.

![Comparison between experimental and theoretical dispersion curves from Bay (2002)](image-url)
2.3.1.4 Applications of the SASW Testing

SASW testing has been employed at many engineering sites. It has been used to determine the material properties of soil and rock types. The SASW method was utilized to find the shear wave velocity and shear modulus of embankment and foundation materials of dams (Bay and Chaiprakaikeow 2006; 2009). These tests used a bulldozer to generate very low frequencies and a very deep profile from the crest of the dam. The shear wave velocity profile to 100 m depth was successfully explored.

SASW testing was performed to find the stiffness of curing Portland cement concrete by Rix et al. (1990). The benefit of using the SASW method was the cement could be tested during the curing state without any intrusion. Changing stiffness could also be monitored throughout the curing process. Subsequently at the final state, values

---

**Fig. 2.28** Assumed shear wave velocity profiles from Bay (2002)
of Young’s modulus calculated from the SASW method and cylinder compression tests agreed very well.

SASW testing was used to determine modulus and thickness of pavement layers (Sheu et al. 1988; Nazarian et al. 1988). Testing by the SASW method could be performed very quickly and the thicknesses of pavement, base, and subgrade were accurately measured without any destruction. Variation of modulus of each layer was also determined from the tests. However, fluctuation in the data caused by reflections from the joints and cracks must be carefully accounted for. Placing source and receiver at proper locations could minimize this effect.

2.3.2 Multichannel Analysis of Surface Waves (MASW)

Multichannel Analysis of Surface Waves (MASW or MCASW) was developed by the Geological team at the University of Kansas in the 90s as an alternative surface wave method (Park 1995; Park et al. 1999). It is a method that uses a wave source and series of receivers, usually twelve or more geophones, to determine shear wave velocity profile. Similar to SASW, the MASW method require three steps. The first is to acquire surface waves from the field testing. The second is to generate a dispersion curve. And the last is to construct a soil profile using a forward modeling.

2.3.2.1 Field Procedures

The MASW method uses a source and series of receivers for field procedure. The source can be either a vertical impact source or a Vibroseis (Park et al. 1996). The source and receiver arrangement of the MASW testing is very similar to that used for body waves - refraction or reflection - tests and is shown in Fig. 2.29.
Several criteria are set for the geophone spacings and offsets in field configuration (Park 1995). Identical to the SASW testing, the nearest distance from the seismic source to the first geophone in the array must be greater than one half of the wavelength to avoid near-field effect (Stokoe et al. 1994). The interval between geophones has to be less than one tenth of the maximum investigated depth:

$$dx \leq 0.1Z_{max}, \tag{2.39}$$

where \( dx = \) geophone spacing, and

\( Z_{max} = \) maximum investigated depth.

Moreover, total length of geophone spread has to be larger than the deepest investigated depth:

$$D \geq Z_{max}, \tag{2.40}$$

where \( D = \) total length of geophone spread.

Number of receiver channels is:

$$N \geq \frac{D}{dx}, \tag{2.41}$$

where \( N = \) Number of receiver channels.

\[\text{Fig. 2.29 Field arrangement of source and receivers of MASW testing from Park (2006)}\]
In the situation that number of channels is less than $D/dx$, additional surveys are required. The receiver array has to be moved to make the total spread length greater than maximum investigated depth.

The raw data acquired from the field using the MASW method, Fig. 2.30, have similar characteristics to the data obtained from refraction or reflection testing. Data obscured by body waves, however, should be ignored from this analysis.

2.3.2.2 Dispersion Curve

Similar to the SASW method, a dispersion curve is generated after obtaining data from the field. However, dispersion curves are estimated from different approach. Transformation theory, by Park et al. (1998), is used in the calculation. Firstly, the time domain signals gathered from the field are Fourier transformed to be frequency domain signals:

$$ U(x, w) = \int u(x, t)e^{iwt} dt, \quad 2.42 $$

where $u(x, t) = $ time domain signal,

$U(x, w) = $ frequency domain signal,

$x = $ offset,

$t = $ time, and

$w = $ frequency in radian,

Equation 2.42 can also be expressed in term of amplitude and phase:

$$ U(x, w) = e^{-i\phi x} A(x, w) \quad 2.43 $$

where $A(x, w) = $ amplitude spectrum, and

$\phi = $ phase.
Fig. 2.30 Raw data of MASW testing at Maxwell AFB in Montgomery, Alabama from Xia (2006)

Secondly, the transformed data are applied with the integral transformation to get $V(w, \varnothing)$:

$$V(w, \varnothing) = \int e^{-i(\Phi-\varnothing)x} [A(x, w)/|A(x, w)|] \, dx,$$  \hspace{1cm} 2.44

where $\Phi = w/c_w$,

$c_w = \text{phase velocity for a given frequency } w$.

Finally, $V(w, \varnothing)$ was transformed to dispersion curves by changing the phase. The peaks of the wavelets from the summation in Equation 2.44 demonstrate the dispersion curve which is shown in Fig. 2.31. Multimode of dispersion curve can be noticed by the peaks of the figure.
2.3.2.3 Forward Modeling

After completing the experimental dispersion curve, the forward modeling is performed to construct a shear wave velocity profile. Similar processing as SASW can be used for this analysis. The optimum shear wave velocity profile can be established from the best fit between the theoretical and experimental dispersion curves.

2.3.2.4 Applications of the MASW Testing

MASW testing has been used for many geological and geotechnical engineering sites to classify subsurface materials by constructing shear wave velocity profile, as SASW testing. The testing of unconsolidated sediments was successfully executed by this method. The study at Fraser River Delta, B.C., Canada by Xia et al. (1999) indicated 15% difference in shear wave velocities between MASW testing and borehole data. The studies in Kansas and Wyoming by Xia et al. (2002) also indicated fairly good agreement between two approaches at 18% and less than 15%, respectively. However, the borehole...
method sampled a much deeper profile than MASW and the differences were measured only down to the depth that MASW could achieve.

Furthermore, MASW has been tested to map the highly consolidated material (bedrock). The study in Olathe, Kansas by Miller and Xia (1999) showed MASW can be used to identify the depth of bedrock from 6 to 23 ft. The study showed that this method can characterize the condition in the bedrock by observing the shear wave velocity. The lower the wave velocity the more weathered the bedrock is. Similar studies to investigate subsurface anomalies were also performed at Tampa, Florida (Miller et al. 1999), at the Indian Refinery in Lawrence, Illinois (Miller et al. 2000a), and at an abandoned mine in Kansas (Miller et al. 2000b). With the MASW method, the investigations were performed quickly and safely and covered a much greater lateral area than the drill hole.

2.3.3 Comparison of SASW and MASW

SASW and MASW are two of the most popular surface wave methods. SASW is a simple test that uses only two to four receivers and a simple Fourier transform for spectral analysis. The advantages of the SASW testing are there is small amount of data to be calculated, and the field experiment is very easy to setup. However, the disadvantage of the SASW is the Fourier analysis uses uniform frequency bandwidth leading to narrow bandwidths at low frequencies that lead to poor resolution of low-frequency waves required for characterizing deeper layers. It also cannot differentiate higher modes of surface waves.

MASW is another test using several receivers for an analysis. The advantages of MASW are that it can characterize different modes of surface waves and it can examine
noise contamination. Disadvantages of MASW are that it requires many sensors which complicates the field testing and it requires lots of data to process.
CHAPTER 3
A NEW SHALLOW REFLECTION METHOD FOR ENGINEERING APPLICATIONS

3.1 Introduction

The seismic reflection method is a geophysical method that uses seismic waves to determine the elastic properties and thickness of subsurface layers based upon the travel-times versus offset of seismic waves propagating through the materials. Three difficulties with using conventional reflection surveys for shallow profiling are addressed in this chapter. First, the conventional method uses many geophones leading to a large amount of data to process. Second, the forcing function from a Vibroseis or shaker source and the motion of the ground are out of phase with each other, leading to poor quality cross-correlations. Third, high frequencies dissipate as waves propagate through a soil medium, degrading the quality of reflected arrivals. This chapter presents a method for seismic reflection that addresses those three issues.

The chapter is separated into six sections: 1) the field procedure, 2) the linear burst chirp source signal, 3) Gabor spectrum filtering, 4) whitening in the frequency domain, 5) phase correction using a reference geophone, and 6) an example of the application of the method at Porcupine Dam.

3.2 Field Procedures

Conventional seismic reflection surveys use many geophones in a regularly spaced array, and reflections are measured using a common center line between source and receivers as shown in Fig. 2.8. The new method uses fewer geophones in an irregular array as shown in Fig. 3.1 where the source, \( S_0 \), is fixed at one location and the receivers,
$R_i$, are set at different offset distances, $x_i$, from the source. A geometric progression is used for receiver spacing. For example if the distance of the source to receiver 1, $x_1$, is 2 ft, the distance from the source to receiver 2, $x_2$, might be $2 \text{ ft} \times \sqrt{2}$, or 2.8 ft. The distance from the source to receiver 3, $x_3$, would be $2.8 \text{ ft} \times \sqrt{2} = 4 \text{ ft}$, and so on.

With this new array of geophones, fewer receivers are required, and less data is acquired. There are two limitations to this approach: first it assumes soil layering is uniform and horizontal, and second, it provides a velocity profile at a single point. These limitations are similar to those of surface wave methods commonly used in engineering.

3.3 Linear Burst Chirp Source Signal

Many types of sources can be used in seismic reflection surveys. This study uses one or more electro-magnetic shakers driven with a linear burst chirp. This source was selected because the frequency content is uniform (white) over a selected frequency band, and it provides sharp cross-correlations. The equation for the linear burst chirp is (Bay 1997):

$$F(t) = F_D \sin 2\pi \left( at + \frac{bt^2}{2} \right) \quad (0 < t < T),$$

where $F(t) =$ burst chirp force function,

$F_D =$ the peak dynamic force,

$T =$ the total time of the chirp, and

$a$ and $b$ control the starting and ending frequencies of the chirp.

The starting frequency, $f_0$, and the ending frequency, $f_f$, of the chirp are:

$$f_0 = a.$$
\[ f_r = (a + bT). \]  

A chirp that has frequency from zero to 50 Hz within 10 s is shown in Fig. 3.2. A synthetic receiver signal is also shown in Fig. 3.3. In order to identify wave arrivals using chirp signals, the source and receiver data are cross-correlated using Equation 2.7. An example of the cross-correlation of the synthetic source and synthetic receivers is shown in Fig. 3.4. After cross-correlation, two wave arrivals are observed as peaks at lag times, one at 1.0 sec and the other at 2.0 sec. In Fig. 3.4 it can be observed that ideal cross-correlations have a sharp arrival or primary lobe, and small and symmetric side lobes.

**Fig. 3.1** Field arrangement of the seismic reflection survey with fewer geophones
Fig. 3.2 Synthetic burst chirp signal with frequency from zero to 50 Hz within 10 sec

Fig. 3.3 Synthetic receiver signal
Fig. 3.4 An example of a cross-correlation of synthetic source and receivers

3.4 Gabor Spectrum Filter

In this procedure, receiver signals are filtered in the time-frequency domain using the Gabor spectrum. This filtering accomplishes two purposes. First, reduces noise by eliminating parts of the signal that are not direct and reflected arrivals. Second, it whitens the signal as discussed in the next section.

A Gabor spectrum filter, shown in Fig. 3.5, is divided into 7 different regions. Region 1, presented as a line, is where the time and frequency occurs in chirp signal. Region 2 is where frequencies are lower than the minimum frequency of chirp signal. Region 3 is where frequencies are higher than the maximum frequency of chirp signal. Region 4 is where times are less than the generated time of the signal, harmonics can be observed within this region. Region 5 is the area of direct arrival. Region 6 is the area of reflected arrival. And Region 7 is the area of post arrival. In order to eliminate signals
that are not direct and reflected arrivals and to reduce noise, only the coordinates of region 1, 5 and 6 are set to 1 while coordinates of other regions are set to 0.

After creating the filter, the signal of the receiver in time domain is transformed into Gabor domain and is then multiplied with the created Gabor spectrum filter. The product represents the cleaner signal, all noise should be eradicated. Then, the product is transformed back into time domain and is cross-correlated with the source. The unclean and clean receivers are shown in Fig. 3.6 and Fig. 3.7, respectively. Noise is eliminated significantly from the signal after filtering. However, there is no major improvement after doing the cross-correlation. The cross-correlation works very well eradicating noises.
Fig. 3.6 Unclean corrected receiver signal at 6 ft offset, Porcupine Dam, Utah

Fig. 3.7 Clean corrected receiver signal at 6 ft offset, Porcupine Dam, Utah
3.5 Whitening

The whitening is a method used to equalize the energy level across the frequency spectrum. In this research, the signals are whitened using 2 procedures: a magnitude replacement and an inverse Q-filtering.

3.5.1 Whitening Using Magnitude Replacement

The magnitude replacement is processed in frequency domain by replacing the magnitude of the existing signal with the magnitude of one, or magnitude of the Vibroseis source. By doing this, energies are balanced throughout frequencies. One experiment was tested using synthetic signals to demonstrate the effect of whitening using magnitude replacement. The source, Fig. 3.2, was the linear burst chirp driving 0-50 Hz within 10 sec. The synthetic receiver was the multiplication of the source and the damping effect, \( e^{-\omega Dt} \), where \( \omega = 2\pi f \), \( D \) was damping coefficient, \( t \) was travel time and \( f \) is frequency. Fig. 3.8 represented the synthetic receiver signal with 2% damp and 1 sec. of travel time. As seen from the figure, higher frequencies were eliminated because of the damping effect. The cross-correlation of the source and the receiver is shown in Fig. 3.9. In order to compensate the loss of energy of high frequencies, the receiver was whitened by replacing the original magnitude with the magnitude of one, throughout the generated frequency, and using the same phase. The comparison of magnitudes of whitening and non-whitening receivers and the phase were shown in Fig. 3.10 and Fig. 3.11 respectively. The whitened receiver signal was then represented in Fig. 3.12 where the compensation of high frequencies was noticeable. The cross-correlation of the source and whitened receiver was also shown in Fig. 3.13. This experiment demonstrated that
the whitening in frequency domain compensated the loss of high frequencies from damping effect.

Fig. 3.8 A synthetic receiver signal with 2% damping effect and 1 second travel time

Fig. 3.9 Cross-correlation between source and non-whitening receiver
**Fig. 3.10** Magnitudes of non-whitening and whitening receivers

**Fig. 3.11** Phase of both whitening and non-whitening receivers
Fig. 3.12 Receiver signal after whitening

Fig. 3.13 Cross-correlation between source and whitening receiver
3.5.2 Whitening Using Inverse Q-filtering

Other whitening method is the inverse Q-filtering. This method is processed in time-frequency domain by creating a similar Gabor filter as Fig. 3.5. However, the regions that contain direct and reflected arrivals, regions 1, 5 and 6 in Fig. 3.5, are set as an energy compensated function, $e^{\omega Dt}$, where $\omega$ was $2\pi f$, $D$ was damping coefficient, $t$ was travel time and $f$ is frequency. Gabor filter using an inverse Q-filtering is shown in Fig. 3.14. By doing so, loss of energy of high frequency waves is recovered as well.

3.6 Phase Correction

One problem encountered with a Vibroseis or shaker source is that the source forcing function is not in phase with the motion of the ground due to the dynamic response of the shaker – ground interface. When receiver signal does not have a consistent phase-shift with the forcing function, the cross-correlation function does not have a single primary lobe at the wave arrival and side lobes are large. This will be

![Gabor spectrum filter to compensate loss energy of high frequency waves](image)

**Fig. 3.14** Gabor spectrum filter to compensate loss energy of high frequency waves
demonstrated in the Porcupine Dam example in the following section.

To solve this problem, a reference geophone is placed in close proximity to the source, but coupled to the ground. The reference geophone is used to measure phase-shifts between the forcing function and the ground motion. Several configurations for reference geophones were used in this work. Fig. 3.15A and Fig. 3.15B show the horizontal and vertical reference geophones that were buried at approximately 1 ft below a shaker source. Fig. 3.15C shows a reference horizontal geophone between two shear wave shakers. All of these configurations were found to work well.

Analysis procedure starts by creating a transfer function between the reference geophone and the source:

$$H_{SR} = \frac{R_0}{S_0},$$ \hspace{1cm} 3.4

where \( H_{SR} = \) transfer function of the source and reference receiver,

\( R_0 = \) reference geophone signal in frequency domain, and

\( S_0 = \) source signal in frequency domain.

Then, the phase correction coefficient, \( C_S \), is created:

$$C_S = \frac{|H_{SR}|}{H_{SR}},$$ \hspace{1cm} 3.5

where \( |H_{SR}| = \) magnitude of the transfer function.

The phase correction coefficient is multiplied with the receiver signals in frequency domain and is transformed back into time domain. Uncorrected cross-correlation and phase corrected cross-correlation are shown in Fig. 3.16 and Fig. 3.17, respectively. A sharper pulse is observed from the cross-correlation after the phase correction.
Fig. 3.15 Three different geometries for reference geophones and shakers

Fig. 3.16 Cross-correlation of the source and uncorrected receiver at 6 ft offset, Porcupine Dam, Utah
3.7 An Example of the Application at Porcupine Dam

A seismic reflection survey using the proposed methodology was performed at the crest of Porcupine Dam in Paradise, Utah. The location of the site, shown in Fig. 3.18, was about 20 miles to the southwest of Utah State University. The dam is an earth-fill dam with height around 160 ft from the crest to the limestone, shale bedrock foundations. The cross-section of the dam is shown in Fig. 3.19. This site was selected because it has uniform soil layers over a strong bedrock reflector.

3.7.1 Field Testing

The tests used two identical magnetic shakers as sources. The source signal was an 8 sec, liner burst chirp, with a frequency span from 2 to 50 Hz as shown in Fig. 3.20. Data were recorded for another 6 sec. after the chirp. 50 time records were averaged.
(stacked) to decrease the environmental noise, and increase the signal-to-noise ratio. Magnitude of the spectrum of the source signal is shown in Fig. 3.21.

Receivers (geophones) used in the tests were Mark Products 1 Hz horizontal geophones shown in Fig. 3.22. One geophone was used as a reference receiver midway between the two shakers as shown in Fig. 3.23. Other receivers were arranged in a linear array, 4 receivers used at a time, as shown in Fig. 3.24. Offsets of 6, 9.5, 12.5, 19, 25, 37.5, 50, 75, 105, 150, 210, and 300 ft were used. The signals from the source and receivers were recorded by a 4 - channel, spectrum analyzer, Agilent Model 35670A, shown in Fig. 3.25. Table 3.1 shows how the testing was stayed.

Fig. 3.18 Location of Porcupine Dam in Paradise, Utah
**Fig. 3.19** Cross-section of Porcupine Dam in Paradise, Utah

**Table 3.1** Summary of Tests at Porcupine Dam

<table>
<thead>
<tr>
<th>Test Set</th>
<th>Channel</th>
<th>Test ID</th>
<th>Spacing, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>Ch 1</td>
<td>S01</td>
<td>Source</td>
</tr>
<tr>
<td></td>
<td>Ch 2</td>
<td>R01</td>
<td>Reference Receiver</td>
</tr>
<tr>
<td>Set 2</td>
<td>Ch 1</td>
<td>R3</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>Ch 2</td>
<td>R6</td>
<td>37.5</td>
</tr>
<tr>
<td></td>
<td>Ch 3</td>
<td>R9</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>Ch 4</td>
<td>R12</td>
<td>300</td>
</tr>
<tr>
<td>Set 3</td>
<td>Ch 1</td>
<td>R2</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>Ch 2</td>
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<td>R8</td>
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<td>Ch 2</td>
<td>R4</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Ch 3</td>
<td>R7</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Ch 4</td>
<td>R10</td>
<td>150</td>
</tr>
</tbody>
</table>
Fig. 3.20  Linear burst chirp source signal with frequency from 2 to 50 Hz within 8 sec

Fig. 3.21  Magnitude of liner burst chirp source signal
Fig. 3.22 Photograph of the Mark Products 1 Hz horizontal geophone

Fig. 3.23 Photograph of the setup of the reference geophone between two magnetic shakers
3.7.2 Analysis Procedures

The raw receiver data gathered from the field testing were analyzed to correct the phase and to compensate attenuated high frequencies. The process of whitening and phase correction are applied simultaneously in terms of a correction filter, $CF_i$. The filter equalizes the amplitude of receiver throughout frequencies and adjusts the phase of receiver signal to match with the phase of the source function by using magnitude of one
over magnitude of the receiver and using the phase of the phase correction coefficient, $C_S$, mentioned in section 3.6. The correction filter is:

$$CF_i(f) = A_i(f)e^{-i\phi Cs} \quad 3.6$$

where

$$A_i(f) = \frac{|1.0|}{|R_i|}$$

$|1.0| = $ magnitude of one,

$|R_i| = $ magnitude of a receiver,

$\phi Cs = $ phase of the source correction coefficient,

$C_S = $ source correction coefficient = $1/H_{SR}$, and

$f = $ frequency

Afterward, all raw receiver data in time domain, $r_i$, were transformed to frequency domain, $R_i$, as:

$$r_i \overset{FFT}{\rightarrow} R_i. \quad 3.7$$

Then the receivers in frequency domain were multiplied with the correction filter to generate magnitude and phase corrected receiver, $R_i'$, in frequency domain as:

$$R_i' = R_i \times CF_i. \quad 3.8$$

The corrected receivers in frequency domain, then, were inverse Fourier transformed back into time domain, $r_i'$, as follows:

$$R_i' \overset{IFFT}{\rightarrow} r_i'. \quad (3.9)$$

Examples of uncorrected and corrected receiver signals, at 6 ft spacing, were shown in Fig. 3.26 and Fig. 3.27, respectively. Same electromagnetic energy is applied at each frequency for the source however, uneven energy is noticed due to non linear dynamic
coupling between the receiver and the ground. The magnitude and phase of corrected receiver were also presented in Fig. 3.28 and Fig. 3.29.

**Fig. 3.26** Uncorrected receiver at 6 ft offset, Porcupine Dam, Utah

**Fig. 3.27** Magnitude and phase corrected receiver at 6 ft offset, Porcupine Dam, Utah
Fig. 3.28 Magnitude of corrected receiver (of Fig. 3.27)

Fig. 3.29 Phase of corrected receiver (of Fig. 3.27)
Finally, each phase and magnitude corrected receiver was correlated with the primary source signal using Equation 2.7. Locations of reflectors were expected from the locations of the peaks of the cross-correlation between the source and corrected receivers.

3.7.3 Results from Testing at Porcupine Dam

The results of the tests at the crest of Porcupine Dam were demonstrated in Fig. 3.30 to Fig. 3.53 by showing comparisons between the uncorrected and corrected cross-correlations. Fig. 3.30 showed a complicated signal of a cross-correlation between the source and uncorrected 6 ft receiver while Fig. 3.31 showed a distinct peak at 1 ms of the cross-correlation between the source and corrected receiver of the same spacing. This vast improvement in the shape of the cross-correlation proved that the corrected data better matches the peaks of the source and the receiver. It also meant that the correction leaded to a better quality and more easily interpreted arrivals signals. Similar improvements were also shown in other spacings that the ringing cross-correlations were simplified to be a unique peak in the figures. However, for further spacings, especially at the spacing of 105 ft, no significant improvement was observed, possibly because of multipath which would degrade the signals. The plots of offset versus time of uncorrected and corrected cross-correlations were shown in Fig. 3.54 and Fig. 3.55, respectively. The surface wave velocities of both figures were around 800 ft/s. Even both presented similar velocities, the biggest peaks of the corrected cross-correlations were fitted linearly better (up to 105 ft spacing) than the uncorrected cross-correlations. Finally, unfortunately that there was no clear evidence of reflections found in this study but vast majority improvement was observed by the improved shape of the cross-
correlations. The conspicuous peaks in the cross-correlations between the source and corrected receivers were more preferable than the uncorrected ones.

**Fig. 3.30** Cross-correlation of the source and uncorrected receiver at 6 ft offset

**Fig. 3.31** Cross-correlation of the source and corrected receiver at 6 ft offset
Fig. 3.32 Cross-correlation of the source and uncorrected receiver at 9.5 ft offset

Fig. 3.33 Cross-correlation of the source and corrected receiver at 9.5 ft offset
Fig. 3.34 Cross-correlation of the source and uncorrected receiver at 12.5 ft offset

Fig. 3.35 Cross-correlation of the source and corrected receiver at 12.5 ft offset
Fig. 3.36  Cross-correlation of the source and uncorrected receiver at 19 ft offset

Fig. 3.37  Cross-correlation of the source and corrected receiver at 19 ft offset
**Fig. 3.38** Cross-correlation of the source and uncorrected receiver at 25 ft offset

**Fig. 3.39** Cross-correlation of the source and corrected receiver at 25 ft offset
**Fig. 3.40** Cross-correlation of the source and uncorrected receiver at 37.5 ft offset

**Fig. 3.41** Cross-correlation of the source and corrected receiver at 37.5 ft offset
**Fig. 3.42** Cross-correlation of the source and uncorrected receiver at 50 ft offset

**Fig. 3.43** Cross-correlation of the source and corrected receiver at 50 ft offset
Fig. 3.44 Cross-correlation of the source and uncorrected receiver at 75 ft offset

Fig. 3.45 Cross-correlation of the source and corrected receiver at 75 ft offset
Fig. 3.46 Cross-correlation of the source and uncorrected receiver at 105 ft offset

Fig. 3.47 Cross-correlation of the source and corrected receiver at 105 ft offset
Fig. 3.48 Cross-correlation of the source and uncorrected receiver at 150 ft offset

Fig. 3.49 Cross-correlation of the source and corrected receiver at 150 ft offset
Fig. 3.50  Cross-correlation of the source and uncorrected receiver at 210 ft offset

Fig. 3.51  Cross-correlation of the source and corrected receiver at 210 ft offset
**Fig. 3.52** Cross-correlation of the source and uncorrected receiver at 300 ft offset

**Fig. 3.53** Cross-correlation of the source and corrected receiver at 300 ft offset
Fig. 3.54 Offset versus time plot of uncorrected cross-correlations

Fig. 3.55 Offset versus time plot of corrected cross-correlations
CHAPTER 4
TIME FILTERED ANALYSIS OF SURFACE WAVE (TFASW)

4.1 Introduction

Fourier analysis in the Spectral Analysis of Surface Waves (SASW) method is equivalent to constant bandwidth of filters leading to non-ideal bandwidths across the frequency band. The Time Filtered Analysis of Surface Waves method (TFASW) is an innovative surface wave (Rayleigh wave) procedure to determine the shear wave velocity profile of a site by using digital filtering that to provide more ideal bandwidths to determine dispersion curves. In general, increasing the bandwidth of a filter improves the signal-to-noise ratio at a given frequency. By using geometric progression bandwidths, with wider bands at low frequencies than used in SASW, better dispersion characterization is obtained. This chapter describes the TFASW including field and analysis procedures.

4.2 Field Procedures

TFASW method is a geophysical method that uses only two to four receivers and similar field procedure for the SASW method. The testing configuration with a source, $S_0$, and receivers, $R_i$, at offsets, $x_i$, is shown in Fig. 4.1. Typically, a geometric progression is used, where $x_i = x_1 a^i$. The longest offset should be 2 - 4 times the required of the profile depth. $x_1$ is typically 1-2 m. Data for TFASW are recorded and stored in the time domain as opposed to the frequency domain for SASW. Time averaging, or stacking is used to improve signal-to-noise ratios. The SASW method uses the difference in phases between two receivers to calculate Rayleigh phase velocities.
The TFASW method, on the other hand, uses the inverse slope of arrival times ($\Delta t$) versus offsets ($x$) to determine wave velocities using band-pass filtered time records.

The TFASW method uses the same in-situ equipments as SASW including various types of vertical wave sources, two to four seismometers or geophones as receivers, and a signal analyzer. The surface waves are generated by vertically exciting the ground surface using different sources to generate different frequencies of surface waves. Low frequency waves are required for deep profiling and high frequency waves to evaluate the shallow layering of the site. With a wide range of frequencies, a complete shear wave velocity profile can be created.

4.3 Time Averaging

TFASW data are averaged in the time domain as opposed to the frequency domain for SASW. The challenge of time averaging is that all measurements must be recorded at exactly the same time relative to the sources. When testing with a 4,500 lb drop weight, the accelerometer triggers when the quick-release drops the weight rather than when the drop weight impacts the ground. Obtaining a consistent trigger measuring the time of ground impact required constructing a physical low-pass filter to isolate the accelerometer from high frequencies generated in the quick-release system. The filter,
shown in Fig. 4.2, was constructed by attaching the accelerometer to a 2.75 in. long by 2.75 in. diameter solid steel bar that is isolated from the drop weight with 0.5 in. thick hard foam rubber. The bar is also surrounded by soft foam to block acoustic transmissions to the accelerometers. The triggering system attached to the top of the drop weight is shown in Fig. 4.3. A transfer function between the trigger accelerometer and an accelerometer attached to the mass was measured to evaluate the effectiveness of the filter. This filter response is shown in Fig. 4.4. The filter effectively attenuates high frequencies without introducing extraneous resonances in the filter. With this filter, the accelerometer is isolated from the high frequency generated by the quick-release system and the time averaging is more effective.

Another option to increase the effectiveness of the time averaging is to use a reference geophone as a trigger. The reference geophone is placed close to the source coupled to the ground. Both systems provided for effective time averaging.
Fig. 4.3 Photograph of physical low-pass filter attached to the 4,500 lb drop weight

Fig. 4.4 Filter response of physical low-pass filter used in drop weight trigger
4.4 Analysis Procedures of TFASW

The TFASW method uses cross-correlations between filtered source signals and filtered receivers to calculate travel-times of surface waves at different frequencies. The analysis procedure used to determine dispersion curves using TFASW are explained in the following section. Forward modeling or inversion procedures used to determine shear wave velocity profiles are the same as for SASW and MASW.

First, all source and receiver time series are filtered using quarter octave, FIR, band-pass filters. The corner frequencies for each pass band filter are:

\[ f_{n+1} = f_n \times \left(2^{1/8}\right), \]

where \( f_n \) = start frequency, and \( f_{n+1} \) = end frequency.

The rectangular band-pass filters used in this study are shown in Fig. 4.5.

An example of the filtering and cross-correlation procedure is shown for one receiver from a test on the USU campus. This complete test is shown in the following sections. Time records from the source and one receiver at an offset of 160 ft are shown in Fig. 4.6 and Fig. 4.7. The band-pass filter with a 12.36 Hz center frequency is shown in Fig. 4.8. Filtered source and filtered receiver, convolutions between raw data and a band-pass filter coefficient, are shown in Fig. 4.9 and Fig. 4.10, respectively.

Next, the filtered source signal is cross-correlated with the filtered receivers signal. Fig. 4.11 show this cross-correlation for the filtered signals in Fig. 4.9 and Fig. 4.10. The travel times, or time shifts occur at the largest peak or trough in the cross-correlation, depended on the relative polarity of the source and receivers. In this case the largest trough represents travel time.
Fig. 4.5  Quarter octave rectangular band-pass filters used in this study

Fig. 4.6  Measured source signal using 4,500 lb drop weight, USU campus
Fig. 4.7 Measured receiver signal at 160 ft offset, USU campus

Fig. 4.8 A rectangular band-pass filter at 12.38 Hz center frequency
Fig. 4.9 Filtered source signal (convolution of Fig. 4.6 and 12.38 Hz filter coefficients)

Fig. 4.10 Filtered receiver signal (convolution of Fig. 4.7 and 12.38 Hz filter coefficients)
For each frequency span, the calculated time shifts are plotted for each receiver relative to its offset. An example of such a plot is shown for the 12.38 Hz filtered USU data is shown in Fig. 4.12. Not all points in such a plot are valid. Points falling in the near-field, and points with low signal-to-noise ratios must be eliminated.

Until a surface wave propagates about 1/2 a wavelength, its motion is not that of a plane surface wave (Wolf 1997), therefore it does not have the same velocity as plane surface wave at that frequency. Therefore, the near-field arrivals should not be used to calculate surface wave velocity. In order to satisfy this far-field criteria:

$$\tau \geq \frac{0.5}{f_c},$$

where $\tau$ = the time shift, and $f_c$ = the filter center frequency.

**Fig. 4.11** Cross-correlation of filtered source (Fig. 4.9) and filtered receiver (Fig. 4.10)
Fig. 4.12  Uncorrected time shift versus offset using 12.38 Hz filter, USU campus

Noise in a signal can cause a significant error in the time shift. Time shifts from noisy signals will fall outside the linear trend, and can be identified as outliers.

Fig. 4.12 identifies near-field and outlier time shifts. Only the valid time shifts are plotted in Fig. 4.13. The velocity of the surface wave, $V_R$ can be calculated using:

$$\text{slope} = \frac{\Delta t}{\Delta s} = \frac{1}{V_R}, \quad \text{4.3}$$

where $\Delta t =$ time difference, 
$\Delta s =$ distance difference, and 
$V_R =$ Rayleigh wave velocity.

This procedure is repeated for each filter to determine the surface wave velocity at each frequency. A dispersion curve which relates the surface wave velocity to either wavelength, or frequency, is then generated as shown in Fig. 4.14.
Fig. 4.13  Linear fitting of corrected time shifts versus offsets using 12.38 Hz filter, USU campus

Fig. 4.14  Dispersion curve analyzed from TFASW, USU campus
4.5 Application of Time Filtered Analysis of Surface Wave at the Various Sites

4.5.1 Application of TFASW Testing at USU Campus, Logan, Utah

TFASW and SASW testing were performed at the park located next to the East Office of Utah State University (USU), Logan, Utah as shown in Fig. 4.15. The site coordinates are 41° 44.639’ North and 111° 48.012’ West. A photograph of the site is shown in Fig. 4.16. The testing was performed along one array oriented in the East-West direction. Two different wave sources, a 4,500 lb drop weight and an instrumented sledge hammer were used for low and high frequencies, respectively. The drop weight was used for offsets of 12 ft up to 320 ft and the hammer was used for shorter offsets of 5 to 20 ft. Table 4.1 summarized the testing sequence.

An example of the magnitudes of signal and noise for the 640 ft offset using the 4500 lb drop weight is shown in Fig. 4.17. High S/N ratios are observed from 4.38 Hz up...
to 25 Hz while low S/N ratio were observed from 0 to 4.38 Hz, around a frequency of 8.76 Hz, and at high frequencies beyond 25 Hz. Examples of the magnitudes of two filtered signals, at 2.6 Hz and 17.51 Hz center frequencies are shown in Fig. 4.18. The data using the sledge hammer are also composed of mixture of clean and poor quality data. Time versus offset plots using drop weight and hammer at different frequencies are shown in Fig. 4.19 to 4.43. Data points eliminated from analysis as being near-field or outlier points are identified.
**Fig. 4.17** Magnitude of signal and noise, USU campus

**Fig. 4.18** Examples of filtered data in each frequency range, USU campus
Fig. 4.19 Time shift versus offset plot at 4.38 Hz filter using drop weight, USU campus

Fig. 4.20 Time shift versus offset plot at 5.21 Hz filter using drop weight, USU campus
Fig. 4.21  Time shift versus offset plot at 6.19 Hz filter using drop weight, USU campus

Fig. 4.22  Time shift versus offset plot at 7.36 Hz filter using drop weight, USU campus
Fig. 4.23  Time shift versus offset plot at 8.76 Hz filter using drop weight, USU campus

Fig. 4.24  Time shift versus offset plot at 10.41 Hz filter using drop weight, USU campus
Fig. 4.25 Time shift versus offset plot at 12.38 Hz filter using drop weight, USU campus

Fig. 4.26 Time shift versus offset plot at 14.73 Hz filter using drop weight, USU campus
Fig. 4.27  Time shift versus offset plot at 17.51 Hz filter using drop weight, USU campus

Fig. 4.28  Time shift versus offset plot at 20.83 Hz filter using drop weight, USU campus
Fig. 4.29  Time shift versus offset plot at 24.77 Hz filter using drop weight, USU campus

Fig. 4.30  Time shift versus offset plot at 29.45 Hz filter using drop weight, USU campus
Fig. 4.31  Time shift versus offset plot at 35.03 Hz filter using drop weight, USU campus

Fig. 4.32  Time shift versus offset plot at 41.65 Hz filter using drop weight, USU campus
Fig. 4.33 Time shift versus offset plot at 49.54 Hz filter using drop weight, USU campus

Fig. 4.34 Time shift versus offset plot at 58.91 Hz filter using drop weight, USU campus
**Fig. 4.35** Time shift versus offset plot at 70.05 Hz filter using drop weight, USU campus

**Fig. 4.36** Time shift versus offset plot at 49.54 Hz filter using sledge hammer, USU campus
**Fig. 4.37** Time shift versus offset plot at 58.91 Hz filter using sledge hammer, USU campus

**Fig. 4.38** Time shift versus offset plot at 70.05 Hz filter using sledge hammer, USU campus
Fig. 4.39 Time shift versus offset plot at 83.31 Hz filter using sledge hammer, USU campus

Fig. 4.40 Time shift versus offset plot at 99.07 Hz filter using sledge hammer, USU campus
Fig. 4.41 Time shift versus offset plot at 117.82 Hz filter using sledge hammer, USU campus

Fig. 4.42 Time shift versus offset plot at 140.11 Hz filter using sledge hammer, USU campus
Dispersion curves from both TFASW and the conventional SASW methods are plotted together in Fig. 4.44. In general, the dispersion curves calculated from both methods agreed very well. The TFASW data have less scatter than the SASW data at low frequencies.

This is a critical improvement, as it increases the accuracy in deep profiling. The calculated shear wave velocity profile of the site is shown in Fig. 4.45. Layer properties are tabulated in Table 4.2. The $V_{s30}$ of the site is 1220 ft/sec classifying the site as NEHRP Site Class C. The boundary between site classes C and D is 1200 ft/sec, therefore this site is on the borderline.

It is interesting to note that velocity is quite uniform with depth. This might be due to a small amount of cementation in the soil fabric.
**Fig. 4.44** Dispersion curves of TFASW and SASW, USU campus

**Fig. 4.45** Shear wave velocity profile of the site, USU campus
### Table 4.2 Layer Properties Determined from TFASW Testing at the USU Campus, Logan, Utah

<table>
<thead>
<tr>
<th>Depth to Top of layer, ft</th>
<th>Layer Thickness, ft</th>
<th>Shear Wave Velocity, ft/sec</th>
<th>Assumed P-wave Velocity, ft/sec</th>
<th>Assumed Poisson’s Ratio</th>
<th>Assumed Unit Weight, lb/ft³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>360</td>
<td>675</td>
<td>0.3</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1050</td>
<td>1965</td>
<td>0.3</td>
<td>105</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1140</td>
<td>2135</td>
<td>0.3</td>
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<td>4</td>
<td>1220</td>
<td>2280</td>
<td>0.3</td>
<td>105</td>
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<tr>
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<td>8</td>
<td>1240</td>
<td>2320</td>
<td>0.3</td>
<td>105</td>
</tr>
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<td>18</td>
<td>1250</td>
<td>2340</td>
<td>0.3</td>
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<td>30</td>
<td>1270</td>
<td>2375</td>
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<td>105</td>
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<tr>
<td>70</td>
<td>70</td>
<td>1280</td>
<td>2395</td>
<td>0.3</td>
<td>105</td>
</tr>
</tbody>
</table>

$V_{s30} = 1220$ ft/sec, NEHRP Site Class C

4.5.2 Application of TFASW Testing at the Salt Lake City and County Building, Salt Lake City, Utah

TFASW and SASW testing were performed at Salt Lake City and County Building in Salt Lake City, Utah on February 6, 2011. The location and a photograph of the site are shown in Fig. 4.46 and Fig. 4.47, respectively.

Tests were performed on three arrays, designated as the North array, the Northwest array and the Southwest array. Triggering problems on the Southwest array resulted in poor time averages, therefore that data was neglected. Reference geophones were used for triggering at the North and Northwest arrays, and good time averaging was achieved.

Sources used were a 4500 drop weight for long offsets, 40 to 400 ft, and an instrumented sledge hammer for short offsets, 10 to 40 ft. The testing sequences are
presented in Table 4.3 and Table 4.4 for the North and the Northwest arrays, respectively. Fig. 4.48 shows an example of a very good agreement between forward and reverse tests using the sledge hammer at the Northwest array. Experimental dispersion curves from SASW and TFASW are shown Fig. 4.49 and Fig. 4.50 for the North array and the Northwest array, respectively. The SASW generated slightly longer wavelengths than the TFASW on both arrays. However, there is less scatter at long wavelengths in the TFASW dispersion curves than the SASW curves. Shear wave velocity profiles of both sites are shown in Fig. 4.51 and Fig. 4.52. Similar shear wave velocity profiles were obtained for both locations. Tabulated layer properties at both arrays are shown in Table 4.5 and Table 4.6. $V_{s30}$ for the North array and the Northwest array are 710 ft/sec and 750 ft/sec, respectively, therefore both sites are classified as NEHRP Site Class D.

![Testing location at Salt Lake City and County Building, SLC, Utah](image)

**Fig. 4.46** Testing location at Salt Lake City and County Building, SLC, Utah
Fig. 4.47 Photograph of TFASW and SASW testings at Salt Lake City and County Building, SLC, Utah

Table 4.3 Sequence of TFASW Testing at the North Array, Salt Lake City and County Building

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Surface Wave Sources</th>
<th>Frequency Span, Hz</th>
<th>Source – Receiver Spacing, ft</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-R1</td>
</tr>
<tr>
<td>1</td>
<td>Drop Weight</td>
<td>0 – 50 Hz</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Drop Weight</td>
<td>0 – 50 Hz</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>Drop Weight</td>
<td>0 – 100 Hz</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Sledge Hammer</td>
<td>0 – 200 Hz</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4.4 Sequence of TFASW Testing at the Northwest Array, Salt Lake City and County Building

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Surface Wave Sources</th>
<th>Frequency Span, Hz</th>
<th>Source – Receiver Spacing, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-R1</td>
</tr>
<tr>
<td>1</td>
<td>Drop Weight</td>
<td>0 – 50 Hz</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>Drop Weight</td>
<td>0 – 50 Hz</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>Sledge Hammer</td>
<td>0 – 200 Hz</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Sledge Hammer</td>
<td>0 – 200 Hz</td>
<td>10</td>
</tr>
</tbody>
</table>
Fig. 4.48 Comparison of Forward and Reverse testing at the Northwest Array, Salt Lake City and County Building

Fig. 4.49 Dispersion curves from the North Array, Salt Lake City and County Building
**Fig. 4.50** Dispersion curves from the Northwest Array, Salt Lake City and County Building

**Fig. 4.51** Shear wave velocity profile from the North Array, Salt Lake City and County Building
Fig. 4.52  Shear wave velocity profile from the Northwest Array, Salt Lake City and County Building

Table 4.5  Layer Properties Determined for the North Array, Salt Lake City and County Building

<table>
<thead>
<tr>
<th>Depth to Top of layer, ft</th>
<th>Layer Thickness, ft</th>
<th>Shear Wave Velocity, ft/sec</th>
<th>Assumed P-wave Velocity, ft/sec</th>
<th>Assumed Poisson’s Ratio</th>
<th>Assumed Unit Weight, lb/ft³</th>
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<td>2</td>
<td>550</td>
<td>1030</td>
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</tr>
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<td>570</td>
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<td>5000</td>
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<td>5000</td>
<td>0.487</td>
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<td>5000</td>
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$V_{s30} = 710$ ft/sec, NEHRP Site Class D
Table 4.6  Layer Properties Determined for the Northwest Array, Salt Lake City and County Building

<table>
<thead>
<tr>
<th>Depth to Top of layer, ft</th>
<th>Layer Thickness, ft</th>
<th>Shear Wave Velocity, ft/sec</th>
<th>Assumed P-wave Velocity, ft/sec</th>
<th>Assumed Poisson’s Ratio</th>
<th>Assumed Unit Weight, lb/ft³</th>
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<td>500</td>
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<td>680</td>
<td>5000</td>
<td>0.491</td>
<td>115</td>
</tr>
<tr>
<td>26</td>
<td>18</td>
<td>710</td>
<td>5000</td>
<td>0.490</td>
<td>115</td>
</tr>
<tr>
<td>44</td>
<td>38</td>
<td>880</td>
<td>5000</td>
<td>0.484</td>
<td>115</td>
</tr>
<tr>
<td>82</td>
<td>18</td>
<td>890</td>
<td>5000</td>
<td>0.484</td>
<td>115</td>
</tr>
</tbody>
</table>

Vs₃₀ = 750 ft/sec, NEHRP Site Class D

4.5.3 Application of TFASW Testing at the Dannon Factory, West Jordan, Utah

TFASW and SASW testing were performed at the Dannon Factory in West Jordan, Utah on January 21, 2011. The location and a photograph of the site are shown in Fig. 4.53 and Fig. 4.54, respectively. Testing was performed at two arrays using the SASW method but only one array using the TFASW method. Sources used in the testing were a 4,500 lb drop weight and a sledge hammer. The testing sequence is shown in Table 4.7.

Good agreement was found between the dispersion curves determined using SASW and TFASW as shown in Fig. 4.55. Again, the long wavelength dispersion curve calculated using TFASW had less scatter than the SASW dispersion curve. The shear wave velocity profile for the site is shown in Fig. 4.56. Tabulated layer properties for the
site are presented in Table 4.8. This site was classified as NEHRP Site Class C with a $V_{s30}$ of 1260 ft/sec.

Fig. 4.53 Testing location, Dannon Factory, West Jordan, Utah

Fig. 4.54 Photograph of TFASW and SASW testings at the Dannon Factory, West Jordan, Utah
Table 4.7  Sequence of TFASW Testing at the Array #2, Dannon Factory, West Jordan, Utah

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Surface Wave Sources</th>
<th>Frequency Span, Hz</th>
<th>Source – Receiver Spacing, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>S-R1</td>
</tr>
<tr>
<td>1</td>
<td>Drop Weight</td>
<td>0 – 50 Hz</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>Drop Weight</td>
<td>0 – 256 Hz</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>Sledge Hammer</td>
<td>0 – 512 Hz</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 4.55  Dispersion Curves from Array #2, Dannon Factory, West Jordan, Utah
**Fig. 4.56** Shear wave velocity profile for Array #2, Dannon Factory, West Jordan, Utah

**Table 4.8** Layer Properties Determined for Array #2, Dannon Factory, West Jordan, Utah

<table>
<thead>
<tr>
<th>Depth to Top of Layer, ft</th>
<th>Layer Thickness, ft</th>
<th>Shear Wave Velocity, ft/sec</th>
<th>Assumed P-wave Velocity, ft/sec</th>
<th>Assumed Poisson’s Ratio</th>
<th>Assumed Unit Weight, pcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>590</td>
<td>1105</td>
<td>0.3</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>550</td>
<td>1030</td>
<td>0.3</td>
<td>105</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>750</td>
<td>1400</td>
<td>0.3</td>
<td>110</td>
</tr>
<tr>
<td>22</td>
<td>24</td>
<td>1500</td>
<td>2805</td>
<td>0.3</td>
<td>110</td>
</tr>
<tr>
<td>46</td>
<td>48</td>
<td>1800</td>
<td>3370</td>
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<td>94</td>
<td>6</td>
<td>2100</td>
<td>3930</td>
<td>0.3</td>
<td>115</td>
</tr>
</tbody>
</table>

$V_{s30} = 1260$ ft/sec, NEHRP Site Class C
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Two different seismic testing approaches, the new shallow seismic reflection method for engineering applications and the Time Filtered Analysis of Surface Wave (TFASW), have been developed in this dissertation. Based on the experimental results, the following conclusions can be made.

5.2 Conclusions and Recommendations
from a New Shallow Reflection Method
for Engineering Applications

There are many challenges in applying the seismic reflection method for shallow profiling. Reflections off of shallow reflections are often obscured by larger magnitude surface waves. Shallow reflections require higher frequency waves than deep profiling. These high frequency waves are subject to large attenuation in soft soil, and there can be high levels of environmental noise at high frequencies. Recent reflection surveys use the Vibroseis as sources because the frequency content is uniform (white) over a selected frequency band, and it provides sharp cross-correlations. However, the problem with the Vibroseis is that the source forcing function is not in phase with the motion of the ground due to the dynamic response of the shaker–ground interface.

This research presents the development of a new shallow seismic reflection method that uses fewer geophones in field testing. Several techniques were used in the new method to improve the quality of the testing. The whitening techniques were used to
compensate for loss energy at high frequencies and a reference geophone was used to correct the phase difference between the source function and the ground motion.

Whitening in frequency domain was evaluated using synthetic signals. Whitening in frequency domain was achieved by replacing the spectral magnitude of the receiver with magnitude of one. By doing so, all energy within the range of desired frequencies was equal (white), compensating for energy losses at high frequencies. Whitening resulted in higher frequencies, and narrower side lobes in the cross-correlations.

Phase difference between the source forcing function and the motion of the ground was corrected by using a reference geophone. The reference geophone is placed in close proximity to the source, but coupled to the ground. It is used to measure phase-shifts between the forcing function and the ground motion. The transfer function between the source and the reference geophone was estimated as a correcting parameter for the phase difference. Effects of phase correction were shown in the results from a field experiment.

A new shallow seismic reflection testing was performed at the crest of Porcupine Dam in Paradise, Utah. The testing used two horizontal Vibroseis sources and four receivers for spacings between 6 and 300 ft. Unfortunately, the results showed no clear evidence of any investigated reflectors from any depth of the site despite correction of the magnitude and phase of the signals. However, the study still showed some improvements in the cross-correlated signals.

The results of the field testing represented an improvement in the shape of the cross-correlations after the magnitude and phase corrections. The results showed distinct primary lobes in the corrected cross-correlated signals. Although, surface wave
velocities of uncorrected and corrected signals were the same, around 800 ft/sec, more consistent maximum peaks were observed in the corrected ones. There was no significant improvement for far offsets, further than 150 ft. The reason could be that there might be some disturbance from undesired signals such as non-subsurface reflectors, i.e., from the dam edges or from non-horizontal reflectors, that could decrease the overall quality of the signals.

Some suggestions are made for improved study of shallow seismic reflection surveys. More field experiments are recommended especially in the sites that can provide strong reflected waves and where scattering and multipath effects are less likely dominate the arrivals. Furthermore, it may be fruitful to examine a higher energy source to determine if it may provide stronger reflectors.

5.3 Conclusions and Recommendations from Time Filtered Analysis of Surface Wave (TFASW)

Time Domain Filtered Analysis of Surface Wave method (TFASW) is a new surface, Rayleigh, wave technique to determine shear wave velocity profile. It is an alternative method to the conventional Spectral Analysis of Surface Waves (SASW). Although both methods use similar field execution, two to four receivers and different types of source, the TFASW is analyzed in time domain instead of frequency domain as used in the SASW method. The SASW method uses Fourier transform for spectral analysis. However, the Fourier analysis uses uniform frequency bandwidth leading to narrow bandwidths at low frequencies that leads to poor resolution of low frequency waves required for characterizing deeper layers. This method used digital filtering that can adjust bandwidth to determine the dispersion curve.
Applications of the TFASW were proved by three tests in different locations, Logan, SLC and West Jordan, in Utah area. The dispersion curves achieved from both TFASW and SASW indicated that these two procedures provided good agreement of dispersion curves. The advantage found for the TFASW was that the dispersion curve analyzed from this method had less data scatter, particularly at lower frequencies, owing to the wider bandwidth used in the analysis. The phase velocity at longer wavelengths was also recovered from the testing in West Jordan. TFASW method, however, had some disadvantages as well. The first was it required more tests than the SASW in order to fill the gaps in the dispersion curve. The second was it had high sensitivity on a computation because small change of the slope in time-offset plot could significantly change the Rayleigh wave velocity. Efficient time averaging was also a necessity, the use of a physical low-pass filter or a reference geophone is recommended.

In order to improve the application of TFASW method, few recommendations can be made. First, software should be developed to automate the analysis. Second variances could be measured to improve in the phase velocity estimations. Third, other types of sources such as Vibroseis should be used with the TFASW method to improve the frequency content of receiver signals. And fourth, the possibility of significant Rayleigh wave energy propagating at higher modes should be included in the analysis procedure. These higher modes can also be included in forward modeling and inversion analyses.
REFERENCES


Braile, L. (2007). *Vibroseis correlation - An example of digital signal processing*. Purdue University, SAGE.


CURRICULUM VITAE

SUSIT CHAIPRAKAIKEOW

EDUCATION

Doctoral Degree (PhD) in Geotechnical and Environmental Engineering  Aug 2012
Utah State University, Logan, Utah  GPA: 3.90
• Awarded research and teaching assistantships

Masters Degree in Geotechnical and Geoenvironmental Engineering  May 2005
Asian Institute of Technology, Pathumthani, Thailand  GPA: 3.63
• His Majesty the King of Thailand’s Scholarship

Bachelors Degree in Civil Engineering  Apr 2003
Mahidol University, Nakornpathom, Thailand  GPA: 3.65
• First class honors

GRADUATE RESEARCH EXPERIENCE

Utah State University, Logan, UT
• Performed more than 10 projects in Utah, Idaho and Thailand in both theoretical and field experimental aspects of the Spectral Analysis of Surface Waves to determine the shear wave velocity profile of soils and rock underlying
• Cooperated with teams of 2 to 50 members in the projects for regular sites to large scale (dam) sites
• Used shear wave velocity to characterize the material beneath the ground surface

Logan Bluff Landslide Project  Aug 2006 - May 2008
Utah State University, Logan, UT
• Monitored and predicted the landslide hazard of the Logan Bluff by investigating piezometers, spring flow and deformation of the slope
• Risk assessment was performed to better understand the factors contributing to the landslides
• Summary of findings and alternative of risk reduction were provided in a project report

Thermal Consolidation of Soft Bangkok Clay Project  Aug 2003 - May 2005
Asian Institute of Technology, Pathumthani, Thailand
• Successfully developed a soft ground improvement technique using heat source and prefabricated vertical drains (PVD) to accelerate the rate of settlement. Rate of settlement significantly increased as well as the strength of the soil
GRADUATE TEACHING EXPERIENCE

Strength of Materials Jan 2009 - May 2012
Utah State University, Logan, UT
  • Taught help sessions six hours/week to assist students in resolving homework problems and assisted with evaluating class exams

Utah State University, Logan, UT
  • Taught 15 students per classes on soil mechanics tests and analysis

Engineering Surveying Jun 2002 - Dec 2002
Mahidol University, Nakornpathom, Thailand
  • Created handout for surveying laboratory class
  • Guided students in surveying field tests

SELECTED PUBLICATIONS

• Buhler, R., Pack, R.T., Bay, J., Chaiprakaikeow, S. (2008), Logan Bluff Landslide Slope Monitoring Program Preliminary Results. 42nd Annual Symposium on Engineering Geology and Geotechnical Engineering, Boise, Idaho

ACTIVITIES/HONORS

• President of Thai Student Association at USU Aug 2006 - Jul 2007
• School of Graduate Studies Honor Roll for Fall Semester at USU 2005
• Recipient of the Thailand Research Fund (TRF) 2003