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SIGNAL PROCESSING FOR
IN-SEAM SEISMIC BASED VOID DETECTION TECHNIQUE

A Thesis in

Mining Engineering

By

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ABSTRACT

Underground coal mining is often carried out in the vicinity of abandoned mine voids filled with hazardous air or water. The aim of this research was to study the problem of underground coal mine void detection by using the in-seam seismic (ISS) technique. This technique refers to methods that utilize artificially generated channel waves trapped in coal seams to locate geologic disturbances and mine voids. ISS is one of the basic geophysical methods for underground survey. The advantage of ISS is that seismic energy in the form of channel waves is better preserved, and therefore seismic waves can be detected over much larger distances compared with those radiating three-dimensionally.

There are many technical problems and theoretical challenges related to the development of the ISS-based void detection technique, especially the acquisition of high quality seismic signals and the interpretation of these signals. First, there are practical issues related to data acquisition in underground coal mines. One has to face the problems of field tests with limited space and irregular source-receiver geometry. Second, there are challenges with data processing because of the underground environment and complex seismic signals. It was necessary to reduce the ambiguity conventionally associated with routine geophysics methods and to find an efficient data processing and void mapping method that is suitable for underground surveys.

An important outcome of this research is the investigation of a set of comprehensive data analysis approaches that are suitable for ISS signals processing. The main contribution of
this research is the development of wavelet analysis based signal processing methods. The wavelet transform, which studies a signal in both the time domain and the frequency domain, was successfully applied to time-frequency analysis, dispersion analysis, and decomposition and reconstruction of channel waves. Wavelet transform, a unique approach introduced in this thesis for the ISS technique, proved to be an efficient tool for signal analysis, including detecting newly merged signals and enhancing reflection signals.

ISS basically uses reflection surveys to detect mine voids, and such reflection signals are much more difficult to identify than transmission signals. Using the Fourier transform, wavelet transform, and other tools, such as the gain controlled stacking method, the reflection signals were enhanced and detected with clear arrivals. Void mapping was realized by a simple and robust method called the elliptical mapping method which is inherently compatible with the complex underground mine conditions and supports simultaneous data processing.

Geophysics methods have been widely used for underground surveys. Among several geophysics approaches for mine void detection, ISS has several distinctive advantages, including high resolution and reliability, long survey distance, and low cost. Thus, the ISS technique and associated signal analysis methods developed in this research appear to provide a very promising technique for mine void detection.
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NOMENCLATURE

The nomenclature presented here is used in general throughout the thesis. The usage shown is applied unless otherwise indicated. A number of symbols or abbreviations, not included here, are used only occasionally and are defined locally in the text where they occur.

2D - two-dimensional
3D - three-dimensional
A - amplitude of the ISS signals
$\alpha_c$, $\alpha_r$ - P-wave velocities of the coal and rock
$\beta_c$, $\beta_r$ - S-wave velocities of the coal and rock
DSP - digital signal processing
dB - decibel
db - Daubechies wavelets
EMM - elliptical mapping method
FFT - Fast Fourier Transformation
$f$ - frequency, the number of oscillations within a unit of time
$ft$ - foot
GPR - ground penetrating radar
ISS - in-seam seismic
In - inch
$k$ - wavenumber, or spatial frequency
MFT - multiple filter technique
MSHA - Mining Safety and Health Administration
$ms$ - microsecond
PGC - programmed gain control
P-wave - Primary waves
psi - pound per square inch
RMS - root mean square
SNR - signal-to-noise ratio
S-wave - Secondary or shear waves
STFT - short time Fourier Transform
  \( T \) - period, the time it takes to complete a cycle of an oscillation
  \( t \) - time
  \( u \) - displacement
  \( v \) - velocity
WT - Wavelet Transform
WTDA - wavelet transform based dispersion analysis method
  \( \omega \) - angular frequency
  \( \lambda \) - wavelength
  \( \rho \) - the density of a medium
\( \nabla \) - Dilatation, is defined as the change in volume per unit volume
  \( \phi \) - father wavelet
  \( \psi \) - mother wavelet
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Chapter 1

INTRODUCTION

1.1 General

1.1.1 Mine Void Detection
Subsurface water or hazardous air filled voids are always serious threats to mine safety and production. Historically, there have been safety, environmental, and economic problems with mine voids, especially abandoned mine voids. Water inundation from an abandoned mine is one of the major safety problems faced by the mining industry. It is estimated that there are nearly 300,000 abandoned coal mines throughout Appalachia, and more than 100 water inundation incidents have been reported at coal mines in the United States alone since 1995 (Gardner and Wu, 2005). The urgency of the problem was highlighted by the Quecreek accident on July 24, 2002, and the dramatic rescue effort of nine miners who were trapped underground for 72 hours due to cutting into a flooded abandoned mine in eastern Pennsylvania (Figure 1.1, MSHA, 2003).
In the past, the underground mine void detection problem has been studied by a variety of techniques, such as longhole drilling, mining geodesy, tecto-mechanical exploration, and geophysical exploration. The commonly employed geophysical methods include surface seismic refraction/reflection, seismic tomography, ground-penetrating radar (GPR), and electrical resistivity (Anderson and Ismail, 2003). Unfortunately, surface seismic surveys with body waves cannot provide enough resolution to detect small dimension underground voids; GPR and electrical resistivity methods are limited by survey depth.
A technique known as the in-seam seismic (ISS)-based mine void detection method was proposed by Penn State researchers to the Mine Safety and Health Administration (MSHA) (Ge, 2006). The objective was to demonstrate a reliable, accurate and cost-efficient mine void detection technique for the mining industry. The demonstrations were carried out at a variety of mines, including an anthracite mine, two trona mines, and two bituminous mines.

1.1.2 Basic Concept of the ISS Technique

The in-seam seismic technique typically refers to methods that use channel waves that are trapped in coal seams. Channel waves, also known as guided waves, are defined as a type of elastic wave propagated and confined in a layer where its energy is trapped. The advantage of using channel waves for mine void detection is that the seismic energy is better preserved and therefore can be detected over much greater distances than seismic energy radiating in three dimensions.

The ISS technique originated from Evison’s in-seam experiment which showed that a coal seam could serve as a waveguide and that “guided waves may find useful applications in mining” (Evison, 1955). Following Evison’s discovery, Krey carried out a systematical study on the theory of the in-seam seismic method (Krey, 1962, 1963, 1976a, 1976b, 1981). During the past fifty years, the in-seam seismic method has grown into a recognized science and engineering discipline. The basic theory and method of the ISS technique were well summarized by Dresen and Ruter (1994).

The ISS-based void detection technique is essentially a reflection technique. The difference between this technique and conventional reflection surveys is the type of
waves utilized. With conventional reflection surveys, body waves are utilized, which can be either P- or S-waves or both, whereas with an ISS technique, Love waves are used. Love waves are a special type of channel or seam wave.

The operational principle of the ISS-based void detection technique is illustrated in Figure 1.2, where both sensors and seismic sources are placed in the middle of the seam. When the seismic source is generated, Love waves will be developed, traveling two dimensionally within the seam. Some of them will be reflected at the void and received by the sensors. The void boundary can then be delineated based on the travel time and travel velocity of the Love waves as well as on the locations of the seismic sources and sensors.

![Figure 1.2 Schematic plan of the test layout for the ISS-based void detection technique. (Both sensors and seismic sources are placed in the middle of the seam. Angled sensor holes are used to enhance polarization analysis.)](image)
1.1.3 ISS Signal Processing

A signal is a physical variable whose value varies with time and space. Signal processing is the processing, amplification, and interpretation of signals, and deals with the analysis and manipulation of signals. Historically, almost all signal processing was done with analog circuits. With the development of computers and sensors, however, it is now commonplace to perform signal processing digitally (Schilling, 2005). One of the most important advantages of digital signal processing (DSP) is the inherent flexibility available with a software implementation such as the MatLAB DSP toolbox.

For ISS signal processing, there are three domains in which signals are most commonly studied. The first is the time domain ($t$). Signals in the time domain, such as the original recorded waveform, show the ground vibration in a time sequence. The second domain is the frequency domain ($f$). Signals can be converted from the time domain into the frequency domain showing the frequency spectrum of the signal. Fourier transforms and digital filtering are the routine methods in this field. The last one proposed in the research for ISS signal analysis is the time-frequency domain ($t$-$f$) using a wavelet transform. The wavelet transform can keep track of both time and frequency information and was found to be very useful and efficient for dispersive channel wave analysis and reflection signal enhancement.

1.1.4 Challenges of ISS-based Void Detection

ISS signal processing is very challenging, as it involves a large array of scientific and engineering problems. The best data processing results usually rely on the combination of a number of methods.
The challenges of ISS signal analysis may be viewed from three aspects. The first is the determination of channel wave velocity. Theoretically, channel waves may travel with a wide range of velocities, from a low value somewhere around 70% of the S-wave velocity of the seam to an upper limit equal to the S-wave velocity of the country rock (Arnetzl and Klinge, 1982). For ISS-based void detection, one is interested in the dispersion curve with the velocity near and below the seam S-wave velocity. The velocities above the S-wave velocity of the seam are highly unstable and have no practical application in the ISS-based void detection technique. Transmission surveys carried out by Penn State researchers showed that the seismic velocity of a thin hard coal seam was highly dispersive, varying from 762 m/s (2500 ft/s) to 2438 m/s (8000 ft/s) with an associated frequency from 200 Hz to 1000 Hz. Therefore, a solid approach to studying the dispersion character of ISS signals and the velocity of channel waves is the key to this research.

The second challenge is the identification of newly arrived signals and the arrival time picking of channel waves. For instance, signals obtained from a reflection survey at a coal mine may include direct P-waves from the roof and floor (the so-called country rock), direct S-waves from the roof and floor, direct S-waves from the coal seam, direct channel waves from the coal seam, reflected P- and S-waves from the coal seam, and a reflected channel wave from the coal seam. These components are often superimposed as the testing site is usually not large enough to separate these signals, which makes the waveforms from field tests very complex. Therefore, a reliable approach to separate channel waves from other signals for arrival time picking is important for this technique.
Finally, the challenge is the identification of reflection signals for void mapping. The ISS void mapping technique is based on a reflection survey. The interpretation of reflection signals is therefore critical for the ISS-based void detection technique. However, ISS experiments have shown that reflection signals were significantly weaker than transmission signals. As a result it was very difficult in some circumstances to identify the reflection signals. Therefore, it was necessary to develop a set of solid data analysis methods that were suitable for reflection study.

1.2 Statement of the Problem

Mine void detection is a complex problem. The conditions faced by mine void detection are very different from the problems conventionally dealt with by geophysical exploration methods. For instance, underground testing sites are not ‘ideal’ for classic reflection surveys which essentially design the locations of sensors and sources for the purpose of better seismic stacking/gathering and signal processing. From the application point of view, a practical void detection method should be feasible for any mining environment, which is often very complex. Because of this, the methods used for ISS experimental design and signal processing have to be robust and flexible.

Another important difference for mine void detection is that the characteristics of in-seam seismic signals are highly site-dependant. The generation and propagation of channel waves are governed by the local conditions of geology as well as the geometry of the testing site. For example, the theoretical calculation of the dispersion curve has to consider the thickness of the coal seam and the shear wave velocities of country rock and
Therefore, there is no ‘always correct’ experimental design and signal processing procedures.

Unfortunately, a review of the history of the in-seam seismic technique shows that these unique challenges of ISS have not gained enough attention. This situation may be attributed to a number of reasons. First, the significance of the operation of underground coal mining on the technique has not been emphasized. From a practical point of view the ISS survey has to match the underground operation and safety requirements. Second, the required site-dependent signal analysis procedures of the ISS technique have not been fully practiced. ISS signals should be interpreted according to the specific circumstances of the testing site, such as the physical property of the coal and the roof and floor, the distribution of the sensors, and the potential seismic ray paths. Third, over the years, the data acquisition system and signal processing methods for ISS have not been updated. With the fast-growing conventional seismology in the geosciences, the development of ISS has been limited in the last two decades. To solve these problems, a systematic approach has to be taken, from experimental design to data analysis and void mapping. One of the important aspects is to develop and utilize new techniques. Such an example is the use of wavelet analysis to solve various problems.

In order to use the ISS technique for void detection, a number of problems have to be addressed. The first is to demonstrate that the ISS technique can be an efficient means for delineating a mine void. In the current study, we are trying to prove that this problem can be solved from two aspects. First, a mine void can be better delineated with the proper experimental design. For instance, a poor experimental design will induce initial system
error and inaccurate void mapping; a good experimental design will improve the sensitivity and provide adequate coverage. Second, a flexible mapping approach, called the elliptical void mapping method, was developed that can deal with any sensor and source array. Void delineation can be achieved with this robust void mapping method with irregular underground geometry.

The second problem is the need to study thoroughly the characteristics of channel waves for a thin anthracite seam. Studies to date have mostly been associated with thick coal seams. However, the properties of channel waves for thin coal seams are very different from those of thick ones. The unique property of channel waves in thin anthracite coal needs to be analyzed in detail.

Third, the most important problem is the detection of reflection signals. The focus of the data processing methods in the ISS literature is transmission data. The ISS-based void detection technique is based on the data from reflection surveys, which are usually very weak. Therefore, the most important task for the improvement of ISS technique should be the efficient identification of reflection signals with proper data processing methods. A solid signal processing approach was the core of this research.

In conclusion, the general goal of this research was to study channel waves in a thin hard coal seam and to develop a set of comprehensive and efficient signal analysis methods. In order to achieve this goal, the strategy taken in this research is summarized as the following:
1. Emphasize the physical properties of channel waves, which require waveform based signal analysis;

2. Develop a comprehensive signal analysis procedure which can study the character of Love waves and efficiently detect reflection signals;

3. Introduce wavelet analysis for ISS signal processing with computer programming.

1.3 Overview of the Thesis

This thesis consists of the following six parts. The first part of the thesis, Chapter 2, is the background on channel waves and a related literature review. A brief review of ISS and other geophysical void detection methods, such as the surface seismic survey, borehole seismic survey, ground penetration radar, and the electric resistance survey, is presented first. The principles of these methods as well as their advantages and disadvantages are discussed. The focus of the chapter is the mathematics and physics of ISS and the associated data analysis methods. A detailed review of pertinent literature is presented in Chapter 2, including a variety of data analysis methods, such as Fourier transform, polarization analysis, and wavelet analysis. A very important character of channel waves is frequency dependent velocity, known as dispersion. The theoretical solution of dispersion for the Harmony site is given in this chapter, which provides a guide for the solution based on actual field data.

Chapter 3 of the thesis is the introduction of data acquisition and ISS field surveys at Harmony Mine, which includes the general considerations of experimental design, such
as experimental layout, the retrievable sensor installation technique, sensitivity analysis, and measures for facilitating data analysis.

Chapter 4 presents signal processing for Harmony Mine with a set of systematic signal analysis approaches, which include visual inspection, polarization analysis, Fourier transform, and digital filtering. The characteristics of channel wave and properties of Airy-phase are discussed in this chapter.

Chapter 5 discusses ISS signal processing with wavelet analysis, which is the core of this thesis. Wavelet analysis was introduced by the author in this research as a novel method for the study of ISS signals. The application includes four general areas: time-frequency analysis, dispersion analysis, wavelet decomposition and reconstruction, and reflection signal enhancement. The application of wavelet analysis is demonstrated using field data.

Chapter 6 discusses how to analyze reflection signals. First, the test arrangement for the reflection survey is discussed. Following this is the analysis of reflection signals. Two reflection surveys are utilized to demonstrate how to enhance and identify reflection signals. Chapter 6 also presents the procedure and results of mine void mapping with the elliptical method. The compatibility and flexibility of the elliptical method is demonstrated by the final mapping results.

The conclusions based on the results of this research and recommendations for future work are given in Chapter 7. Several important supplemental materials for this research, such as a detailed mathematical proving procedure and selected computer programming, are given in a number of appendices.
Chapter 2

BACKGROUND AND LITERATURE REVIEW

2.1 General Introduction

There are many subsurface voids such as washouts, underground mine workings, natural limestone caves, and sinkholes. While some of the shallow voids might represent general civil engineering concerns and can be detected and delineated using nonintrusive geophysical techniques, void detection for an underground mine with considerable depth can be very challenging.

Void detection is a classic problem for underground mine production and safety. This chapter presents a literature review of various subjects associated with the current study, which includes an overview of void detection techniques, the theory of the in-seam seismic (ISS) technique, the concept of channel waves, and signal analysis methods.

2.2 Mine Void Detection Methods.

A variety of techniques have been used or investigated for void detection, including longhole drilling, geodesy, tecto-mechanical exploration, and geophysical exploration. The most commonly employed geophysical methods include seismic refraction, seismic reflection, seismic tomography, ground-penetrating radar (GPR), and electrical resistivity. The following is a brief review of these methods.
2.2.1 Longhole Drilling

Longhole drilling uses boreholes drilled into the coal seam to acquire direct information about the coal seam ahead. The advantage of this method is its reliability. It shows the ‘truth’ of the coal seam with direct contact. For this reason, it is also called “ground truth drilling”. A limitation of this technique is that it cannot be used in water-dissolvable seams, such as trona. The main disadvantage of the method is its relatively high cost. The other problem of the method is the risk of causing an inundation if the test borehole could not be sealed. According to an experienced worker, 30% of their longhole drilling has some water problems (Bohan, 2006).

2.2.2 Surface Seismic Methods

Surface seismic methods refer to those with which both sources and sensors are located on the surface. Figure 2.1a illustrates a seismic refraction survey, where acoustic signals are generated at source locations and recorded by sensors after critical refraction. A velocity profile is generated by the recorded travel time information. A special case of refraction survey is a reflection survey where signals are reflected at the interface directly (Figure 2.1b).
2.2.3 Borehole Seismic Method

The borehole seismic method uses boreholes to house sensors and sources. This method normally utilizes multiple boreholes. Figure 2.2 is an illustration of this method, where signals are generated at source locations in the source borehole and recorded by sensors in the receiver borehole. The seismic data are statistically analyzed and a velocity and attenuation cross-sectional model is generated to study the area between the source and the receiver boreholes. Tomography is a method widely used for analyzing the data from cross-hole surveys.
In order to achieve a better resolution, a vertical borehole may be utilized to deploy sources for seismic reflection surveys (Figure 2.3). The reflected signals are received by the sensors mounted on the surface. This method is called reverse vertical seismic profiling (RVSP).

Figure 2. 2 Cross-hole seismic survey.

Figure 2. 3 Reverse vertical seismic profiling (RVSP) survey.
2.2.4 Ground Penetration Radar and Electric Resistance Survey

Besides these conventional seismic methods, two others that have been widely tried are Ground Penetration Radar (GPR) and electric resistance survey. A GPR survey is illustrated in Figure 2.4, where an electromagnetic (EM) signal is generated at station locations along the length of the GPR profile, and the reflected EM energy is recorded by a mono-static antenna. The information is used to generate a GPR profile and can be transformed into a 2-D velocity model. The major problem of GPR is the detection range, which is very short and thus not practical for mine void detection.

![Figure 2.4 Ground Penetration Radar survey](image)

The principle of the electrical resistivity survey is explained in Figure 2.5. A pair of electrodes, $C1$ and $C2$ is mounted on the surface and the current is induced. The potential difference ($\Delta V$) between paired voltmeter electrodes $P1$ and $P2$ is measured. A resistivity and depth profile can be generated by the survey.
2.2.5 In-Seam Seismic Method

The conventional seismic methods, as discussed earlier, are convenient and cost effective. The main problem with these methods for mine void detection is lack of resolution. Mine voids, usually with dimensions of a few meters (seam height), are difficult for conventional seismic methods to detect because the length of the body waves used by these methods is on the order of dozens of meters. According to T. Krey (1963), seismic body waves originated and observed underground within the mine are hardly suitable for detecting faults, as the rock on both sides of the fault plane has the same physical properties nearly everywhere. Also, Krey mentioned that big differences only appear where the coal seam is disconnected from the fault, but since such places constitute only a very small percentage of the surface of the whole fault plane, body waves really have no reasonable chance of success.
The method that could potentially overcome the resolution problem is the in-seam seismic (ISS) method, which uses waves trapped in coal seams for void detection. The technique originated from a finding by Evison some 50 years ago that a coal seam could serve as a waveguide and that “guided waves may find useful applications in mining” (Evison, 1955). Krey suggested the use of in-seam seismology for underground coal mine discontinuity detection. In a set of experiments conducted nearly 40 years ago, he demonstrated the waveguide concept of channel waves and explained it theoretically. His experiments indicated that (Mason, 1980):

- hard coal embedded in country rock forms a seismic wave guide;
- energy coupled into a coal seam is constrained to propagate in a set of a few modes only;
- the corresponding signals are strongly dispersive.

Krey’s original observations have been confirmed in experiments conducted in coal mines worldwide. Based on Krey’s innovative ideas, researchers began to investigate the ISS method with in situ studies and various modeling techniques. Extensive theoretical studies and field investigations started in Great Britain during the mid-1970s (Buchanan, 1981, 1983). Publications appeared during the 1970s from the United States (Stas, 1974). Australia began extensive work on the ISS method in the late 1970s (Asten et al., 1980).

The late seventies was an important period for the development of the ISS technique. The first generation of analog equipment was replaced by modern digital instruments, which greatly enhanced data acquisition and processing capability (Mason, 1980, Buchanan, 1981). Theoretically, more detailed studies on the physics of channel waves were carried
out, including dispersion analysis (Mason, 1980), absorption of Love wave (Krey, 1982), attenuation and anisotropy of channel waves (Buchanan, 1983), velocity analysis, polarization characteristics, signal recompression and migration analysis, and numerical modeling of Love wave propagation (Kelly, 1983), etc.

Numerical modeling is an important part of seam wave research. The finite difference method was used to study dispersion curves, amplitude-depth distributions, and the scattering of Love waves (Buchanan, 1986). Li analyzed the Frequency-dependent Q-estimation of Love-type channel waves with a symmetric and homogenous, three-layered linear elastic model (Li et al., 1995). Li also developed a deterministic pure phase shift filter to extract the fundamental mode from multimode Love waves (Li, 1997).

2.3. Theory of the In-Seam Seismic Method

2.3.1 Channel Waves
A channel wave is propagated in a layer where the energy is trapped, which is also called a guided wave (Sheriff, 1984). According to the principle of wave propagation, total reflection will occur at the boundaries when the reflection angle is larger than the critical one. Energy is prevented from escaping the channel when total reflection occurs at the boundary. There are two situations to generate channel waves. First, the layer has a lower velocity than the velocity on either side. Second, one side is a free surface (air) so that the reflectivity coefficient is almost one. There are three major sources of channel waves: surface waves on the earth’s surface, ocean channel waves at a depth of around 1000 meters below the sea surface (Stein, 2003), and channel waves in coal seams.
In a homogeneous isotropic coal seam, seismic waves propagate as channel waves along the rock-coal-rock sequence. The trapping of seismic waves within the seam leads to a two-dimensional propagation of channel waves (Krey, 1963, Dresen, 1985). The seam waves decay much more slowly than the body waves, and therefore the ISS technique, which utilizes this type of wave, has a much better chance of succeeding in mine void detection.

For an in-seam seismic survey, the energy under study is trapped in the seam and spreads two-dimensionally as shown in Figure 2.6. The energy decay due to geometric spreading in this case is identical to the one for cylindrical waves. It is not difficult to observe that the decay of the energy for the ISS study is much slower. At an equal distance, the energy level for the ISS study will be $r^{1/2}$ times stronger than that for the traditional reflection survey. For instance, the ISS signal level will be 10 times stronger than body wave signals if the distance is just 30.5 m (100 ft).

![Figure 2.6 Geometrical spreading associated with a cylindrical source: (a) cylindrical source, (b) wave propagation from a cylindrical source (after Hardy, 2003).]
2.3.2 Mathematics and Physics of Channel Waves

A coal seam embedded in country rock constitutes a low velocity channel for elastic wave propagation. If a source is generated in the middle of the coal seam, elastic waves propagate from the source in all directions throughout the coal. By simplifying the seismic source, the medium and the spread of waves, the development and propagation of seismic waves along the coal seam and surrounding country rock can be described mathematically.

2.3.2.1 Wave Equations

The mathematical expression of channel waves can be derived strictly from the theory of elasticity and Newton’s law of motion. Considering the displacement field, \( u \), which is a function of both time \( (t) \) and space \( (x) \), a one-dimensional scalar wave equation can be written as

\[
\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 u(x,t)}{\partial t^2} \tag{2.1}
\]

where, \( v \) is the speed of wave propagation. A general solution for wave equation (2.1) is a harmonic wave,

\[
u(x,t) = Ae^{i(\omega t \pm kx)} = A\cos(\omega t \pm kx) + Ai\sin(\omega t \pm kx) \tag{2.2}\]

where \( u \) and \( A \) are displacement and amplitude functions, respectively. The parameters used in the equations above are defined as follows:

- Period \( (T) \): the time it takes to complete a cycle of an oscillation.
- Frequency \( (f) \): the number of oscillations within a unit of time. \( f = 1/T \)
- Angular frequency \( (\omega) \): also named circular frequency. \( \omega = 2\pi f \)
- Velocity ($v$): the speed of the wave propagation. $v = \lambda / T$
- Wavelength ($\lambda$): the distance of two corresponding points in a cycle. $\lambda = v \cdot T$.
- Wavenumber ($k$): also called spatial frequency, oscillation frequency in unit distance. $k = 2\pi / \lambda = \omega / v$

For an isotropic elastic medium, a three-dimensional vector wave equation can be represented as

$$\nabla \cdot \left( \rho \nabla \cdot \mathbf{u}(\mathbf{x}, t) \right) + \nabla \times \left( \mu \nabla \times \mathbf{u}(\mathbf{x}, t) \right) = \rho \frac{\partial^2 \mathbf{u}(\mathbf{x}, t)}{\partial t^2}$$

(2.3)

where, $\lambda$ and $\mu$ are elastic constants, $\rho$ is the density of the medium. $\nabla$ (Dilatation) is defined as the change in volume per unit volume $\theta = \Delta V / V$,

$$\theta = \frac{\Delta V}{V} = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = \nabla \cdot \mathbf{u}$$

(2.4)

From equation (2.3), the harmonic plane wave solution, similarly to equation (2.1) in one dimension, is given as

$$\phi(\mathbf{x}, t) = A \exp\left(i(\omega t \pm k_x x \pm k_y y \pm k_z z)\right)$$

(2.5)

2.3.2.2 P- and S- waves
There are two basic types of waves, P-wave and S-wave. The P-wave is usually defined as a wave in which particle motion is in the direction of wave propagation. It is also called compressional wave, primary wave, pressure wave, and longitudinal wave. The S-wave is defined as a wave in which particle motion is perpendicular to the direction of wave propagation. It is also named shear wave, secondary wave, and transverse wave.

The displacement field $\mathbf{u}(\mathbf{x}, t)$ can be expressed by two other functions, compressional wave scalar potential $\phi(\mathbf{x}, t)$ and shear wave vector potential $\mathbf{\psi}(\mathbf{x}, t)$. 
\[ \mathbf{u}(x, t) = \nabla \phi(x, t) + \nabla \times \psi(x, t) \]  
(2.6)

The above expression is known as the **Helmholtz Decomposition**, which separates scalar and vector potentials.

Substituting Equation (2.6) into Equation (2.4) gives two wave equations:

\[ \nabla^2 \phi = \frac{1}{\alpha^2} \frac{\partial^2 \phi}{\partial t^2} \]  
(2.7)

where, \( \alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}} \) is the velocity of the P-wave;

\[ \nabla^2 \psi = \frac{1}{\beta^2} \frac{\partial^2 \psi}{\partial t^2} \]  
(2.8)

where, \( \beta = \sqrt{\frac{\mu}{\rho}} \) is the velocity of the S-wave.

**P-wave**

The P-wave is the type of wave whereby the particle motions are in the same direction as the propagation. Considering a plane wave propagating in the y direction, equation (2.7) becomes

\[ \phi(y, t) = A \exp(i(\omega t - ky)) \]  
(2.9)

Substituting Equation (2.9) into Equation (2.6),

\[ \mathbf{u}(y, t) = \nabla \phi(y, t) = (0, -i\lambda, 0) \exp(i(\omega t - ky)) \]  
(2.10)

The volume change of the medium,

\[ \nabla \cdot \mathbf{u}(y, t) = -k^2 A \exp(i(\omega t - ky)) \]  
(2.11)

Equation (2.11) indicates that the volume change is nonzero. So there is compression and dilatation in the direction of propagation (Figure 2.7).
Figure 2. 7 P-wave, particle motion is parallel to wave direction.

**S-wave**

The S-wave is the type of wave where the particle motions are perpendicular to the direction of the wave propagation. From Equation (2.8), the harmonic plane waves are given as

\[ \psi(x,t) = (A_x, A_y, A_z) \exp(i(\omega t - k_x x - k_y y - k_z z)) \]  

(2.12)

Substituting Equation (2.12) into Equation (2.6),

\[ \mathbf{u}(y,t) = \nabla \phi(y,t) = (-ikA_x, 0, ikA_z) \exp(i(\omega t - ky)) \]  

(2.13)

The displacement field \( \mathbf{u} \) has a zero component in the \( y \) direction and nonzero components in the \( x \) and \( z \) directions.

The volume change of the medium is

\[ \nabla \cdot \mathbf{u}(z,t) = \nabla \cdot (-ikA_x, 0, ikA_z) \exp(i(\omega t - ky)) = 0 \]  

(2.14)

This means that there is no volume change in the direction of propagation because the dilatation is zero (Figure 2.8).

Figure 2. 8 S-wave, particle motion is perpendicular to wave direction without volume change.
An important character of the S-wave is its polarization. S-waves polarized in the horizontal plane are called SH-waves. If polarized in the vertical plane, they are called SV-waves.

### 2.3.2.3 Love Wave

Named after A.E.H. Love (1863-1940), the Love wave, also called the Evison wave, results exclusively from the constructive interaction of SH-waves (Edwards et al., 1985). The development of the interference systems contributing to the Love seam wave in terms of multiple reflected and refracted rays is shown in Figure 2.9.

![Schematic development of interference systems of SH-waves leading to the formation of the Love channel wave, where A is the leaky mode range, and B and C are the normal mode range (after Dresen and Ruter, 1994).](image)

For simplicity, it is assumed that the country rock and coal seam are perfectly elastic, homogeneous and isotropic, and that all interfering body waves are plane waves. Figure 2.10 shows a symmetrical rock-coal-rock mode which assumes that the roof and floor have similar properties and have a higher velocity than the coal seam. The P- and S-
wave velocities of the coal and rock are noted as $\alpha_c, \beta_c$ and $\alpha_r, \beta_r$, respectively; $d$ is half of the coal seam thickness and $j$ is the incident angle.

Figure 2. 10 A symmetrical rock-coal-rock mode of a coal seam.

From Equation 2.13, the SH wave displacement in the coal seam can be written as the sum of an up-going and a down-going wave:

$$u_y(x, z, t) = A_1 \exp(i\omega t - k_x x - k_z r_{\beta_r} z) + A_2 \exp(i\omega t - k_x x + k_z r_{\beta_r} z)$$  \hspace{1cm} (2.15)

where, $A_1$ and $A_2$ are the amplitude of the up going and down going waves, $r$ is defined as the ratio of the vertical to horizontal wavenumber, for example, $r_{\beta_r} = k_z(\beta_r) / k_x(\beta_r)$. Because these waves are totally reflected at both boundaries, $A_1$ equals to $A_2$. Based on Snell’s Law, for an SH wave incident on both sides at a critical angle, $j = \sin^{-1}(\frac{\beta_c}{\beta_r})$ and from Equation 2.8 we can get: $r_{\beta_r} = \sqrt{\frac{\alpha_c^2}{\beta_r^2}} - 1$.

**Boundary Condition**: at the rock-coal boundary, $z = d$, the displacement and stress must be continuous at the interface for any $x$ and $t$. For displacement,

$$A_1 \left[ \exp(-ik_x r_{\beta_r} d) + \exp(ik_x r_{\beta_r} d) \right] = A_1 \exp(-ik_x r_{\beta_r} d)$$  \hspace{1cm} (2.16)

For stress,
\[
\mu_c (-ik_r r_{\beta}) A [\exp(-ik_r r_{\beta} d) - \exp(ik_r r_{\beta} d)] = \mu_c (-ik_r r_{\beta}) A, \exp(-ik_r r_{\beta} d) 
\]
\[(2.17)\]

Combining equations (2.16) and (2.17),

\[
\tan(k_r r_{\beta} d) = \frac{\mu_c r_{\beta}}{\mu_c r_{\beta}} 
\]
\[(2.18)\]
or

\[
\tan \left[ \frac{\omega d \sqrt{1 - \frac{1}{c_x^2}}}{\beta c_x^2} \right] = \frac{\mu_c}{\mu_c} \sqrt{1 - \frac{1}{\beta c_x^2}} 
\]
\[(2.19)\]

The phase velocity is the solution of

\[
k_r r_{\beta} h = \tan^{-1} \left( \frac{\mu_c r_{\beta}}{\mu_c r_{\beta}} \right) + \frac{n}{2}, \pi, n=0, 1, 2,... 
\]
\[(2.20)\]

This is usually called the dispersion equation for Love channel waves. \(n\) is the mode ordering number, where \(n = 0\) is the first mode or fundamental mode and \(n = 1, 2, \ldots\) are higher modes.

### 2.3.2.4 Dispersion Analysis

Dispersion is a phenomenon that causes the separation of a wave into spectral components with different wavelengths, due to a dependence of the wave's speed on its wavelength. In a non-dispersive wave medium, waves can propagate without deformation. For instance, sound waves in air are nearly non-dispersive. A channel wave in a coal seam is, however, frequency dependent and therefore dispersive.

There are generally two sources of dispersion: physical dispersion, which comes from a frequency-dependent response of a material to waves; and waveguide dispersion or geometrical dispersion, which occurs when the speed of a wave in a waveguide depends on its frequency.
For a graphic solution of Equation 2.20, let us first define
\[
\tau = d \sqrt{\frac{1}{\beta_c^2} - \frac{1}{c_x^2}}
\]  
(2.21)

Substitute it into Equation 2.20,
\[
\tan \left[ \omega d \sqrt{\frac{1}{\beta_c^2} - \frac{1}{c_x^2}} \right] = \tan[\omega \tau] = \mu_c \sqrt{\frac{1}{c_x^2} - \frac{1}{\beta_r^2}} = \mu_c \sqrt{\frac{1}{c_x^2} - \frac{1}{\beta_r^2}} \cdot \frac{d}{\tau}
\]
(2.22)
or
\[
\tan[\omega \tau] = d \cdot \mu_c \cdot \mu_c \sqrt{\frac{1}{c_x^2} - \frac{1}{\beta_r^2}} \cdot \left( \frac{1}{\tau} \right)
\]
(2.23)

Now, the left side of Eq. 2.23 is a tangent function of \(\tau\), and the right side is a hyperbolic function of \(\tau\). A graphic solution of the equation is presented in Figure 2.11. This solution is based on the seam condition at the Harmony Mine defined as follows:

\[
\begin{align*}
&d = 0.61 \text{m} = 2 \text{ft}, \\
&\beta_c = 1097 \text{ m/s} = 3600 \text{ ft/s}, \\
&\beta_r = 2438 \text{ m/s} = 8000 \text{ ft/s}, \\
&\mu_c = 1506 \text{ kg/m}^3 = 94 \text{ lb/ft}^3, \\
&\mu_r = 2323 \text{ kg/m}^3 = 145 \text{ lb/ft}^3.
\end{align*}
\]

The calculation was carried out by a MatLAB program. The program code and some examples are given in Appendix A.
(At 3000 Hz, $n=0$, $v=1106$ m/s (3630 ft/s); $n=1$, $v=1195$ m/s (3919 ft/s); $n=2$, $v=1458$ m/s (4784 ft/s))

Figure 2.11 An example of a graphic solution of the dispersion relation for Love waves for a simple rock-coal-rock model. Physical parameters are from Harmony Mine Site II.

Phase velocities can be obtained directly from the graphic solution. Group velocities can be derived from phase velocities by the following equation,

$$U = \frac{dv}{dk} = \frac{d(ck)}{dk} = c + k \frac{dc}{dk} \quad (2.24)$$

The phase and group velocities for the first (fundamental) mode of Love waves are listed in Table 2.1, and the associated dispersion curve is presented in Figure 2.12. The dispersion curves characterize the frequency and velocity relation for the channel waves developed under the specific condition. Once such a curve is established for a mine site, it provides a direct guideline for data interpretation.
Table 2.1 Phase and group velocity calculation

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<th>Frequency (Hz)</th>
<th>Phase Velocity (c) (ft/s)</th>
<th>Group Velocity (U) (ft/s)</th>
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<th>$dc$</th>
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<td>3559</td>
<td>3.2529</td>
<td>0.1762</td>
<td>-6</td>
</tr>
<tr>
<td>2000</td>
<td>3664</td>
<td>3548</td>
<td>3.4297</td>
<td>0.1768</td>
<td>-6</td>
</tr>
<tr>
<td>2500</td>
<td>3642</td>
<td>3535</td>
<td>4.3130</td>
<td>0.8833</td>
<td>-22</td>
</tr>
<tr>
<td>3000</td>
<td>3630</td>
<td>3559</td>
<td>5.1927</td>
<td>0.8797</td>
<td>-12</td>
</tr>
<tr>
<td>3500</td>
<td>3620</td>
<td>3551</td>
<td>6.0749</td>
<td>0.8822</td>
<td>-10</td>
</tr>
<tr>
<td>4000</td>
<td>3617</td>
<td>3593</td>
<td>6.9485</td>
<td>0.8736</td>
<td>-3</td>
</tr>
</tbody>
</table>

* Minimum group velocity.
The minimum of the group velocity is called the Airy-phase. In the case of the Harmony Mine, it is 1048 m/s (3437ft/s) at a frequency of 400 Hz. The Airy-phase is a special part of Love waves related to extrema in a group velocity dispersion curve. The rate of the energy decay for the Airy-phase is $x^{-1/3}$, which is much smaller than the rate of $x^{-1/2}$ associated with other wave groups. Therefore, the Airy-phase is preferred in ISS surveys for the detection of faults in coal seams. An example of the Airy-phase is shown in Figure 2.13.
The theoretical study of the dispersion characteristics is important for the experimental design, data acquisition, and signal analysis. It is, however, necessary to note that these studies are often based on highly simplified models. The real world is in general much more complex. At the Harmony Mine, for instance, the seam is not flat, rather rolling with the geological structures; the seam thickness is highly unstable, varying from 3 to 6 feet at the test site; and there is a highly fractured coal layer at the bottom of the seam. All these factors will have a significant impact on the actual dispersion properties of the signals.

2.4 Signal Analysis

Signal analysis for seismic data involves a wide range of issues and there are many signal processing methods available. A comprehensive review of these issues and methods is beyond the scope of the thesis. The focus of this review will be wavelet related problems since the main contribution of the author is the development of the wavelet based techniques for processing the ISS data.
2.4.1 Fourier Transform and Digital Filtering

Seismic signals are a physical variable recorded as a sequence of time. With modern data acquisition techniques, these signals are digitized after recording and stored in a digital format known as digital signals. Techniques for processing digital signals have widespread application in the modern world. One of the fundamental and most commonly used methods is digital filtering, which is a typical example of applications of the Fourier transform developed by Fourier in 1807. Generally speaking, any waveform can be viewed as a combination of sinusoidal waves of various amplitude, frequency and phase. The standard Fourier transform has the form

\[ F(w) = \frac{1}{\sqrt{2\pi}} \int e^{-iwt} f(t) \cdot dt \]  

(2.25)

With the Fourier transform, a signal in the ‘time domain’, \( f(t) \), can be transformed to the ‘frequency domain’, \( F(w) \), or vice versa. The importance of the Fourier transform is that it allows one to view seismic data from two different perspectives: the time domain and frequency domain. It also offers a convenient and efficient means for data processing. For instance, if one would like to eliminate the signals with certain frequencies from recorded data, they must first transfer the data from the time domain to the frequency domain, delete unwanted frequencies with a suitable digital filter, and transfer the data back into the time domain.

2.4.2 Windowed Fourier Transform

A shortcoming of the Fourier transform is that it does not provide any time information about the frequency when signals are transferred from the time to the frequency domain. However, often the information on a local frequency and phase content is even more
important. Such an example is the arrival time picking of the seismic signal. Physically, one would expect a dramatic change in frequency at the time a new signal arrives. One of the methods to address this problem is to use the Short time Fourier transform (STFT) or windowed Fourier transform (WFT). The mathematical expression for the STFT is given by Equation 2.26:

\[(T^{\text{win}} f)(w, t) = \int f(s) \cdot g(s - t) e^{-iws} \cdot ds\]  

With this technique, the information on time-localization is obtained by first windowing the desired part of the signal and then carrying out the Fourier transform on this particular part. The concept of this technique is shown in Figure 2.14, where one can obtain “snap-shots” of the time-frequency behavior of the signal by moving the center of the window along the time axis.

![Figure 2.14 Windowed Fourier transform](after Daubechies, 1992).

### 2.4.3 Wavelet Transform

The wavelet transform is a tool that cuts up data, functions or operators into different frequency components, and then studies each with a resolution matched to its scale (Daubechies, 1992). The wavelet transform is particularly useful for analyzing signals
which can be described as aperiodic, noisy, intermittent, and transient (Paul, 2002). During the past several decades, wavelet transform analysis has been used to investigate a wide range of physical phenomena, from signal analysis and image compression to climate analysis, financial indices, heart monitoring, etc. Actually, the wavelets techniques were first applied in geophysics to analyze the data from seismic surveys carried out for oil and mineral explorations (Boggess & Narcowich, 2001). Therefore, from the application point of view, seismology can be regarded as the birthplace of modern wavelet methods.

According to Daubechies, wavelets are a relatively recent development in applied mathematics. They first got attention in the 1980s and have since grown at an explosive rate. One reason for their success is that wavelets are a fairly simple mathematical tool with a great variety of possible applications. As a consequence of these interdisciplinary origins, wavelets appeal to scientists and engineers of many different backgrounds. Wavelets have already had exciting applications in signal analysis and numerical analysis among many other applications.

Wavelet transforms have advantages over traditional Fourier transforms for representing functions that have discontinuities and sharp peaks. The mathematical expression for the wavelet transform is given by Equation 2.27:

\[
(T_{\text{wav}} f)(a, b) = |a|^{-1/2} \int f(t) \cdot \psi\left(\frac{t-b}{a}\right) \cdot dt
\]  

(2.27)

One similarity between the wavelet and windowed Fourier transforms is that both Eq.2.26 and Eq.2.27 take the inner products of \( f \) with a family of functions indexed by
two labels, $g_{w,t}^w(s) = e^{-i\omega_0} \cdot g(s-t)$ in Eq.2.26, and $\psi_{a,b}^w(s) = a^{-1/2} \psi\left(\frac{s-b}{a}\right)$ in Eq.2.27.

The difference between these two methods is that the STFT function $g_{w,t}^w$, regardless of the value of w, has the same width; the wavelet function $\psi_{a,b}^w$ has time-widths adapted to its frequency. Therefore, the wavelet transform is more capable of “zooming in” on very short high frequency phenomena, such as transients in signals.

One of the major characteristics of ISS signals is multiple arrivals during a short time period. The wavelet transform can keep track of time and frequency information at the same time. This function is therefore extremely useful for identifying the arrival of new signals, which is a critical problem for the ISS-based void detection technique.

A seismic waveform is bounded in both frequency and duration. Wavelet transforms provide an alternative to more traditional Fourier transforms, which are used for analyzing waveforms. The Fourier transform converts a signal into a continuous series of sinusoidal waves, each of which is of constant frequency and amplitude and of infinite duration. In contrast, wavelet transforms convert a signal into a series of wavelets. Most real-world signals, such as reflected P- and S- waves in a coal seam, have a finite duration and abrupt changes in frequency.

An example is given in Figure 2.15. With the help of wavelet transform, the relationship between time and frequency can be clearly demonstrated.
2.4.4 Polarization Analysis

Polarization analysis is a basic approach for identifying different wave types composing the data recorded during the ISS test, including refracted P- and S-waves, transmitted S-waves, and Love waves. Krey (1963) suggested that the axes of the geophones should be given different directions to record the different components of seismic motion, and, preferably, two geophones should be used with opposite polarization.

Hodogram analysis is one of the methods used to study signal polarization in terms of the particle motion with time. The concept of this technique is illustrated in Figure 2.16, where the amplitudes of a two-component transmission record were plotted. The first window (17-26 ms) contains the P-wave which is sensitive to the vibration whose direction is towards the source. The second and third windows show emerging S-waves. Windows 6 and 7 are dominated by channel waves.
Figure 2. Hodogram analysis of an in-seam recorded transmission seismogram supports the identification of different wave groups and different wave types. (after Millahn, 1980).
EXPERIMENTAL DESIGN AND DATA ACQUISITION

Experimental design is the first and an very important step for the ISS-based void detection survey. The purpose of experimental design is to create the best test situation for acquiring high quality signals and to construct a stable mathematical system for data analysis. A good performance data acquisition system, including sensor installation, is also the prerequisite of acquiring high quality signals.

3.1 Testing Site

The use of Harmony Mine as an initial testing and demonstration site for the development of the ISS-based void detection technique had several advantages. Firstly and most importantly, the mine, like many others, faces the problem of void detection as it will approach an abandoned mine in several years. The identification of a reliable void detection technique has become a real issue for the mine. Secondly, the site is suitable for testing the ISS-based void detection technique as the coal is competent and roof and floor are very strong. Thirdly, the short distance from the Penn State campus to the mine site, and enthusiastic support by the mine owner and mine management were also pluses.

The Harmony Mine is an anthracite mine located near Mt. Carmel in Mount Carmel Township, Northumberland County, Pennsylvania, United States (Figure 3.1). It is located 141 km (88 miles) northwest of Philadelphia and 114 km (71 miles) northeast of Harrisburg. The harmony mine is a modern efficient underground coal mine, which
began its operations in 1988. The room-and-pillar mining system is utilized to extract the coal (Figure 3.2). The annual production of the mine ranges between 160,000 and 195,000 tons for the past 10 years, making it the largest underground anthracite mine in North America.

Figure 3.1 Geographic location of Harmony Mine.

Figure 3.2 Two testing sites at the Harmony Mine.
A total of three field tests were carried out at the mine at two different locations, Site I and Site II. Figure 3.2 is a mine map showing the approximate locations of these two test sites. Site I was located in the middle of a long pillar, which was about 18 m (60 ft) wide. Site I was the initial test site, utilized mainly for testing several techniques developed for ISS-based void detection. Site II was a much larger pillar with a width of 46 m (150 ft). This site is more representative in terms of the size. Because of this, it is the focus of this study.

### 3.2 Experimental Design

Experimental design is the first and probably the most critical step for the ISS-based void detection technique. For a comprehensive discussion of this issue, readers may refer to Ge (2006). Many factors, including both theoretical considerations and practical problems, have to be taken into account. The basic objective of experimental design is to create the best test situation for acquiring high quality signals. Other important considerations include providing an adequate coverage for the area to be surveyed, facilitating data analysis, and creating a stable mathematical system. In this section, four components of experimental design will be discussed, namely: testing layout, data acquisition system and sensors, sensor installation, and seismic sources.

The ISS technique is carried out in an underground environment which could adversely affect the reflection survey in many ways. In order to achieve the objectives of experimental design, there are many factors to be considered. First, one has to answer several basic design questions, such as how to cover the survey area, how to create a stable survey system, and how to link the experimental design and data analysis. As these
design principles are basic and should be implemented for all applications, they will be discussed first. The second aspect is how to apply these basic principles for given conditions. Here practical experience plays a very important role. The second part of this chapter, therefore, discusses how to handle a variety of practical issues.

3.2.1 Adequate Coverage of the Target Area

The first concern of the experimental design is to provide adequate coverage for the area to be surveyed. Adequate coverage has a two-fold meaning. First the entire area targeted for evaluation has to be covered. For some cases, this may not be possible because of the restrictions on the source-receiver locations. When this is the situation, the section which can be surveyed should be specified. The second aspect of adequate coverage is survey resolution. For instance, if irregular entries within mine boundaries are a concern, such as that attributed to the Quecreek incident, the required survey resolution should be less than the entry width.

3.2.2 Stability of Test Setup

Errors in input data, such as signal arrival time and signal travel velocity, are inevitable. One of the design objectives is to establish a stable system which will minimize the impact of input errors. The sensitivity analysis studies the sources of input errors and their impact to the final solution. An illustration of the relationship between travel distance and the geometry of sensor, source and reflector is shown in Figure 3.3, where $A$ and $B$ denote the location of source and receiver, respectively.
In Figure 3.3, $f$ is the source – receiver distance. The void is represented by line $OB'$. Line $OB'$ is defined by two parameters: $\alpha$, the angle with the survey line; and $h$, the distance from the void to A. The signal travel distance is given as

$$L = \sqrt{4h^2 + f^2 + 4hf \sin \alpha}$$

(3.1)

If there is a change in signal travel distance, $\Delta L$, due to velocity or timing errors, the corresponding error for the void location is

$$\Delta h = \frac{\sqrt{4h^2 + f^2 + 4hf \sin \alpha}}{4h + 2f \sin \alpha} \Delta L$$

(3.2)

where $\Delta h$ is the void location error. Although it appears from the above equation that the void location error is a complicated function of $h$, $f$ and $\alpha$, it is not difficult to find that the dominant term for the equation is $f$, the source – receiver distance. Therefore, the stability of a survey system is controlled by the source – receiver distance. In other words, a short source-receiver distance should be used, if possible, in order to reduce the impact
of initial errors. Refer to Appendix B for a detailed discussion.

### 3.2.3 Design of Angled Sensors

One of the critical data analysis issues for ISS-based void detection is identification of P- and S-wave arrivals. The ability to detect P- and S-wave arrivals is critical for general data analysis. One of the problems specially associated with ISS void detection is multiple signal arrivals within a short time period. For instance, the first arrived wave group in reflection surveys is actually composed by P- and S-waves from roof, floor and seam, as well as transmitted channel waves. In order to analyze these arrivals, one has to know how to identify P- and S-wave arrivals.

A basic physical means for identifying P- and S-wave arrivals is the use of three-dimensional (3D) sensors. Each 3D sensor has three sensor elements oriented in an orthogonal layout (Figure 3.4 a). With this arrangement, one may be able to identify P- and S-wave arrivals by comparing the signals in three directions (Figure 3.4 b).

![3D sensor configuration](image1)

![Waveforms by a 3D sensor](image2)

Figure 3.4 sensor configuration and signals detected by a 3D sensor (after Hardy, 2003).
A major difficulty with the use of 3D sensors for void detection is the problem of suitable field installation. Conventionally, 3D sensors have to be installed in cement filled boreholes. This technique provides an intimate sensor-to-rock coupling. However, it also prevents removal of the sensor for use at other locations. The relatively high cost of 3D sensors, $1000 – 2500 each, makes their use prohibitive for ISS-based void detection.

A simple and efficient solution for this problem is to use the pseudo-2D sensor arrangement (Ge, 2006). With this arrangement, sensor holes are drilled in pairs. These pairs are oriented orthogonally, with the tips of the boreholes very close to each other. The operational principle of the pseudo-2D sensor is shown in Figure 3.5. With the given arrangement, the right sensor of each pair is more sensitive to the P-waves while the left one is more sensitive to S-waves.

![Figure 3.5 Using angled sensor pairs for polarization analysis.](image-url)

When the angled sensor pairs are used for identifying P- and S-waves, the ideal arrangement is that one component is oriented in the direction of the expected wave and
the other is oriented in the transverse direction. In practice, the arrangement has to be made based on both the potential signal direction and site conditions.

3.3 Testing Site Design

Site II is a 46 m (150 ft) wide pillar, located within a room and pillar development area near the portal of the mine (Figure 3.2). The layout for this test site is illustrated in Figure 3.6.

Figure 3.6 Experimental layout of the test site. The setup includes a sensor array (AB), three source sections (1, 2, 3) for transmission surveys and two source sections (4 and 5) for reflection surveys. Details of the sensor array (AB) are given at the bottom of the figure.
There were one sensor array and five source sections. The sensor array was located at the lower right corner of the pillar, which was consisted of 16 sensor holes. All boreholes were drilled in the center of the seam to a depth of 1.5 m (5 ft) from the face. This arrangement was used to avoid near-face fracture zones, one of the measures necessary for improving the coupling effect. Angled sensor holes were used to facilitate polarization analysis. The sensors installed in paired sensor holes S4/S5, S8/S9 and S12/S13 were used to simulate biaxial sensors.

The two source locations at the south side of the pillar (4 & 5) were used for reflection surveys. A total of 16 reflection surveys were carried out using these two locations. It is interesting to note the irregular sensor and source locations. These source sections and the sensor array were not in a straight line. Source section 4 was significantly off the sensor line. In fact, even the sensor line itself was not straight. Furthermore, the spacing of the sensors was highly irregular. For the ISS-based void detection, it is sometimes impossible to avoid irregular sensor and source locations and irregular sensor spacing. These irregularities have an important impact on the mapping method to be used for void detection.

The three source locations on the north side of the pillar (1, 2, & 3) were used for transmission surveys. Sites 4 & 5 which were designed for reflection surveys also provided transmission data since they were not on the same line as the sensor section. With the transmission data available from all five source locations, the test site was well covered in terms of both ray directions and ray traversing areas.
3.4 Data Acquisition

3.4.1 Sensor Installation

One of the main challenges for the ISS-based void detection technique is how to acquire high frequency signals over large distances. In US, the minimum width of the barrier pillars separating two mines is 45 m (150 ft), which implies that the system has to be able to detect high frequency signals with a minimum travel distance of 90 m (300 ft) in order to make the technique practical.

There are two main reasons for using high frequency signals. First, the frequency of Love waves for the thin coal seam at the Harmony Mine was estimated in the range of 300–800 Hz with the Airy-phase of 500 Hz, which is much higher than the signal frequency used for conventional geophysical and ISS applications.

Second, high frequency signals are a necessary condition for high resolution surveys. Figure 3.7 illustrate the relationship between the wavelength of seismic signals and the diameter of mine voids. In order to detect an object, the wavelength much be sufficient short.

![Figure 3.7 Relationship between wavelength and dimension of mine void.](image-url)
One of the important conditions for acquiring high quality and broadband signals is the quality of the coupling. Conventionally, this would require grouting the sensor in the borehole. However, to be economically feasible, the sensors must be retrievable so that they can be used repeatedly at the same or another location. A retrievable sensor installation technique was therefore developed for the project (Ge, 2006). The technique enables the sensor to effectively detect high frequency signals yet is simple and convenient for both installation and retrieval operations. The technique has been used for several of the ISS-based void detection projects. Sensors installed in the prescribed manner have exhibited predictable, consistent, and repeatable performance.

The retrievable uniaxial sensor consists of two parts, a sensor body and a screw assembly (Figure 3.8). The screw assembly is the anchor of the sensor, grouted at the bottom of the sensor hole.

Figure 3.8 A retrievable uniaxial sensor consisting of a sensor body and a sensor screw anchor.

Figure 3.9 is a schematic illustration of a retrievable sensor installed at the bottom a borehole. An initial design had only one paper cup (Cup-1) to hold the epoxy or resin. However, at Harmony Mine Site I, a sensor was lost in the borehole because there was
some resin leaked out of Cup-1 and the sensor itself was strongly stuck to the borehole well. With this lesson, another paper cup (Cup-2) was incorporated in order to protect the sensor.

Figure 3. 9 Schematic illustration of a retrievable sensor installed at the borehole bottom.

The retrievable sensor installation technique involves five major aspects: epoxy, installation devices, simulation facility, field work procedure, and pull-out test. Epoxy is used to grout the sensor anchors at the borehole bottom. Installation devices are the hardware used for sensor installation, which include an epoxy mixing device, installation assembly and installation tool kit. The simulation facility at Penn State Rock Mechanics Lab was used for sensor installation training and evaluation of in-situ anchorage strength. The field work procedure involves the work in sensor-hole preparation and sensor installation. The pull-out test is a quantitative means to assess various parameters related to sensor installation, which is the basic technique used for developing the retrievable sensor installation technique.
3.4.2 Data Acquisition System

A 16-channel ESG Hyperion seismic monitoring system was used for data acquisition. The system has a 16-bit resolution with a maximum sampling rate of 40 kHz per channel. During the operation, one channel, connected to a wire-breaking device, was used for triggering. The other fifteen channels were used for recording seismic signals. A sampling rate of 20 kHz was used for data recording at the Harmony Mine.

Sensors utilized for the study were ESG A1030 accelerometers, uniaxial sensors with a sensitivity of 30 V/g and a flat response (plus or minus 3db) within the bandwidth 50 to 5000 Hz. The sensors were 10 cm (4 in) long and 2.54 cm (1 in) in diameter.

A noticeable feature of the overall monitoring system is its broadband capability, ranging from 50 to 5000 Hz. This is very different from the frequency range normally used for conventional reflection surveys. This capability is necessary for several reasons. First, the coal seam at the Harmony Mine is thin, 1.37 m (4.5 ft) on average. Considering that the period of Love waves is in the same order of the seam height, the expected signal frequency of Love waves would be at least several hundred. In fact, the typical frequency for the Airy-phase at the mine site is 400 – 600 Hz, and some are close to 1000 Hz. Second, the signal frequencies for the body waves transmitted through the country rock are even higher, typically in a range of 2000 – 3000 Hz. A system which can record these high frequency signals is extremely important for data analysis. Third, if the system is used for void detection for a non-coal mine condition, where in-seam body waves have to be used, the expected signal frequency could be even higher. For instance, the signals
used for void detection in trona mines have a typical frequency range of 3000 – 5000 Hz (Ge, 2006).

### 3.4.2 Seismic Sources

Detonation caps, and dynamite in the amount of 40, 80, and 120 grams were used as the seismic sources. The use of 80 and 120 grams appeared too strong for the site, resulting in saturation of the recording system. The explosives were installed at the bottom of specially prepared blasting holes. These holes were 3.8-cm (1.5 in) in diameter and 1.2-m (4 ft) long, drilled in the middle of the seam at right angles to the coal face. Each blasting hole was sealed by a 61-cm (24 in) long plug of stemming clay, which was tightly tamped against the explosive charge of the borehole bottom.

### 3.5 Summary

Practical issues and design principles for field experimental tests were discussed in this chapter. At Harmony Mine Site II, five blasting sections and one sensors section were designed. The data acquisition system used by Penn State ISS void detection project team featured a broadband capacity and retrievable sensor installation. This part of work was extremely important to obtain the high quality data necessary for the project as well as for this research.
Chapter 4

SIGNAL PROCESSING AND THE CHARACTERISTICS OF LOVE WAVES

4.1 General

As discussed in Chapter 2, the velocity and frequency of Love waves are governed by the physical condition of the testing site. In this chapter, the site condition at Harmony Mine, an anthracite mine with a thin coal seam, will be discussed. Following this, the signal processing methods and the characteristics of Love waves will be presented.

The characteristics of Love waves can be studied from different aspects. A seismic signal could be converted from the time domain to the frequency domain, and to the wavelet domain. Signal analysis methods are usually defined in one of these domains. For instance, visual inspection and polarization analysis are based on the signals in the time domain; digital filtering is based on the signals in the frequency domain; wavelet transform is based on the signals in the wavelet domain, or so-called time-frequency domain. Therefore, it is necessary and convenient at this point to study the character of Love waves along with the discussion of the associated signal analysis methods. Wavelet analysis, a very important part of this research, will be discussed in detail in the next chapter.

4.2 Site Condition

There are four main types of coal: lignite, sub-bituminous, bituminous, and anthracite. Anthracite is well known for having the highest BTU among all types of coal. Physically,
anthracite differs from other types of coal by its greater hardness and higher density. The associated geological condition is also quite different. An anthracite mine usually has a strong roof and floor strata, due to the high temperature and high pressure in geologic history that were necessary for the metamorphosis of anthracite coal. The physical properties of a coal seam and country rock are the main factors affecting ISS signals.

The characteristic of Love waves is site dependent. The development and propagation of Love waves are affected by many factors. The important ones are the physical properties of both the coal seam and the country rock, such as density and velocity, and the geometric factors, such as seam thickness and flatness. Because of this, the site condition at the Harmony Mine will be discussed first.

The anthracite seam at the mine site varies from less than 0.3 to over 4 m (1 - 13 ft) thick, averaging 1.37 m (54 in). The seam is overlaid by 69 to 122 m (255 - 400 ft) of overburden. The immediate roof and floor is a light-gray to yellowish-brown conglomerate sandstone with a uniaxial compressive strength greater than 82 MPa (12,000 psi). The immediate roof conglomerate is 9 to 20 m (30 - 65 ft) thick and the floor conglomerate is 3 m (10 ft) thick. The mine is level in pitch, operating on the apex of an anticline. Table 4.1 is a brief summary of the conditions at Harmony Mine Site II.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test site layout</td>
<td>46 m(150 ft) wide pillar, good for transmission and reflection</td>
</tr>
<tr>
<td>Coal Seam condition</td>
<td>1.2 m (4 ft) thick coal with highly fractured layer at bottom</td>
</tr>
<tr>
<td>Roof material</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Floor material</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Noise condition</td>
<td>Low</td>
</tr>
<tr>
<td>Water presence</td>
<td>Yes</td>
</tr>
</tbody>
</table>
4.3 Signal Analysis Methods

Signal analysis is a complicated problem which involves a large array of scientific and engineering topics. The analysis of the ISS data often requires using many different methods. The focus of this chapter is on the routine data analysis procedure used in this project, which includes visual inspection, polarization analysis, Fourier transform, and digital filtering.

4.3.1 Visual Inspection

The first step of the data analysis was the visual inspection of the waveforms. In general, it started with the transmission data, which were acquired from the transmission surveys. The transmission signals from the reflection surveys could also serve this purpose. Figure 4.1 shows such an example where the P-wave, the S-wave, and the Airy-phase of the Love wave can be physically identified.

![Figure 4.1 A transmission signal with clear P-wave, S-wave and Airy-phase of Love waves by means of visual inspection.](image)

A very interesting phenomenon was noted in that the characters of the seismic waves were significantly affected by the blasting locations. This effect is shown in Figure 4.2 by the waveforms of five events originating from five different survey locations previously indicated in Figure 3.6.
Figure 4. Original waveforms of five events: Event 22, 38 (from Demonstration Test) 43, 72 and 89.
Figure 4. 3 Original waveforms of five events (Continued)
The main characteristics of these five events are briefly summarized in Table 4.2. The differences in these waveforms were significant. From case 1 to case 5, the Love waves become stronger, and the refracted high frequency body waves became weaker.

<table>
<thead>
<tr>
<th>Case</th>
<th>Event (Location)</th>
<th>Blasting Source</th>
<th>Relative angle to sensor location</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H2E38(T22)</td>
<td>Cap</td>
<td>0º</td>
<td>No obvious trend of Love waves or Airy-phase; Strong signals from roof and floor with very high frequency.</td>
</tr>
<tr>
<td>2</td>
<td>H2E 22 (T10)</td>
<td>1 inch</td>
<td>20º</td>
<td>No obvious trend of Love waves. Only three channels have Airy-phase; strong signals from roof and floor with very high frequency.</td>
</tr>
<tr>
<td>3</td>
<td>H2E43 (T1)</td>
<td>Cap</td>
<td>45º</td>
<td>Strong Airy-phase for first 5 channels; a trend of Love waves is obviously.</td>
</tr>
<tr>
<td>4</td>
<td>H2E72(R11)</td>
<td>1 inch</td>
<td>70º</td>
<td>Strong and sharp Love waves with obviously Airy-phase.</td>
</tr>
<tr>
<td>5</td>
<td>H2E89(R8)</td>
<td>1 inch</td>
<td>90º</td>
<td>Strong and sharp Love waves with obviously Airy-phase.</td>
</tr>
</tbody>
</table>

A possible explanation for this phenomenon is that the P-wave and the S-wave generated by blasting have a different orientation of propagation. According to Vanbrabant et al. (2002), the P- and S-wave generated by blasting have a special angle of propagation.

For a continuous, homogeneous, elastic field, the theoretical solution of this problem has been presented by Rossmanith et al. (1997).

Figure 4.3 shows the angles of the P- and S-waves and the blasting borehole. Equations 4.1 and 4.2 give the theoretical solution of the angles between the borehole and the wavefront of the P- and S-waves.
Figure 4.4 Wavefront of the P- and S- wave by a finite charge in a continuous, homogeneous, elastic field (after Rossmanith, 1977).

\[ \alpha = a \sin \left( \frac{C_P}{C_d} \right) \]  \hspace{1cm} (4.1)

\[ \beta = a \sin \left( \frac{C_S}{C_d} \right) \]  \hspace{1cm} (4.2)

where, \( \alpha \) and \( \beta \) are the angles between the borehole and the wavefront of the P- and S-waves; \( C_P \) and \( C_S \) are the velocity of the P- and S-waves, and \( C_d \) is the velocity of the detonation. Suppose the velocity of the detonation \( C_d \) is 4000 m/s (13123 ft/s), the velocity of the P-wave \( C_P \) and the S-wave \( C_S \) in anthracite coal is 1219 m/s (4000 ft/s) and 2438 m/s (8000 ft/s), respectively. By equations 4.1 and 4.2,

\[ \alpha = a \sin \left( \frac{C_P}{C_d} \right) = 41.8^\circ \]  \hspace{1cm} (4.3)

\[ \beta = a \sin \left( \frac{C_S}{C_d} \right) = 19.5^\circ \]  \hspace{1cm} (4.4)

This calculation result indicated that the shear waves are more likely to propagate at the direction perpendicular to the orientation of the blasting borehole. This theoretical solution supports the actual phenomenon in Figure 4.1 where the Love waves in case 4 and 5 are very strong and the P-waves in cases 1 and 2 are very strong.
4.3.2 Polarization Analysis

Polarization analysis is a method to identify different wave types including refracted P- and S-waves, transmitted S-waves, and Love waves. Hodogram analysis is one of the methods used to study signal polarization in terms of the particle motion with time. One of the main purposes of the polarization analysis is to identify wave types, such as P- and S-waves. In general, polarization analysis can be used to enhance the differences in the transverse and radial components of the ground motion.

An example was demonstrated by Event 89 (Figure 4.4), where sensors S8 and S9 were a pair of angled sensors and could be considered a pseudo 2-dimensional sensor. The corresponding signals recorded by these two sensors are shown in Figure 4.5.

Figure 4.5 A pair of angled sensors, S8 and S9, simulates a 2D sensor.

The lower part of this figure shows the hodograms of these two channels, with the x axis representing the direction of Ch9 (S8) and the y axis representing the direction of Ch10 (S9). The seven windows are plotted with the same scale to display the ground motion and energy distribution at a different time.
The first and last two windows are associated with very weak noise. The second contains P-waves polarized vertically and refracted at the coal-rock interface. In the third window, the refracted S-waves superimposed on the refracted P-waves and a trace of particle motion was close to circular. The fifth window is dominated by Love waves which were polarized horizontally. Figure 4.6 is an enlarged version of window 5 in Figure 4.5. The Airy-phase of the Love wave is highly polarized in one direction. With a Hodogram analysis, it was evident that the love waves arrived after 0.085 second. Signals before this time point were body waves. The programming coded with MatLAB is given in Appendix C.
Figure 4. 7 Ground motion at S8_S9 from 90~100 ms. (window No. 5 of Figure 4.5) was dominated by the Airy-phase of the Love waves.

4.3.3 Fourier Transform and Digital Filtering

The Fourier transform, developed by Fourier in 1807, is one of the most commonly used methods for signal processing. Any waveform can be analyzed as a combination of sinusoidal waves with different amplitudes, frequencies, and phases. Digital filtering is based on the idea that, if the frequency spectrum of a signal under study is different from that of background noises, one may eliminate the noise by ‘blocking’ the frequencies associated with the noise in the process of Fourier transformation. In order to use the digital filtering technique, the key is identification of the frequencies associated with the signals as well as those associated with the noise. If they are different, appropriate filters can be used to separate signals from noise.
Signals recorded during an in-seam seismic test are a mixture of many different wave groups. A convenient and efficient means to identify these wave groups is to analyze their frequency spectra using the Fourier transform. In general, the frequency of the P- and S-wave signals from the roof and floor is higher than the frequency of the Love waves for an ISS test. An example is given in Figure 4.7, where part (a) is the transmission signals whose spectral analysis is shown in part (c). With the FFT analysis, we can see that there are two separate signals in the frequency domain. The first is from 100 to 500 Hz, the second is from 500 to 1200 Hz. With a 500 Hz lowpass filter as shown in part (d), we get a signal with a clean channel wave as shown in part (b).

Figure 4.8 An example of Fourier transform and a low-pass filter for Event 17 Channel 3.
4.3.4 Short Time Fourier Transform

The Fourier transform converts a signal from the time domain into the frequency domain and provides a very convenient and efficient means for data processing. For stationary signals, the Fourier transform is sufficient. However, for non-stationary signals such as seismic signals, which vary with frequency in the time domain, it is important to retain time information. An approach to solving this problem is called the Short Time Fourier Transform (STFT). The MATLAB signal processing toolbox provides a function known as the *Specgram* that provides the time-dependent Fourier transform. The *Specgram* uses a sliding window to compute the windowed discrete-time Fourier transform of a signal. The spectrogram is the magnitude of this function (MatLAB Signal Processing Toolbox, 2004).

Figure 4.8 shows the result of the STFT calculation for the signals demonstrated in Figure 4.7. It is a three-dimensional expression of a signal in terms of time (x-axis), frequency (y-axis) and amplitude. Amplitude is shown by color, whereby a darker color means a higher energy. The high frequency components (from 1000 to 4000 Hz) are from the roof and floor, and the low frequency components (from 200 to 800 Hz) are from the coal seam. The advantage of the STFT over the conventional Fourier transform, as shown in this example, is that the time information of the signal is saved after the Fourier transform. The STFT is very useful for identifying newly arrived signals for ISS data processing.
Figure 4.9 Specgram of Event 17 Ch3 using a short time Fourier transform.

4.4 Characteristics of Love Waves

The ISS-based void detection technique relies on the travel time information of Love waves. Unlike body waves, for which the velocities can be assumed as constant for most engineering applications, the travel velocity of Love waves is a function of the associated signal frequency, a phenomenon known as dispersion. Since the dispersion characteristics are governed by site conditions such as seam height, and densities and S-wave velocities
are associated with seam and country rock, field studies are essential in order to acquire this site-sensitive information.

4.4.1 Love Waves Observed at the Harmony Mine Site II

In order to determine the dispersion characteristics of Love waves associated with the Harmony Mine site, a detailed transmission survey was carried out. This included a total of 28 surveys with sources located at the five general locations (Figure 3.6). Love waves were observable from all the surveys and most were well defined. Such an example is Event 89, a reflection survey by design. The layout of this survey is shown in Figure 4.9, where R8 denotes the location of the seismic source. Two sets of ray paths are shown in the figure. One (AC) is for the transmitted Love waves from R8 to the sensor array, and the other (ABC) is for the Love waves reflected from the other side of the pillar. The focus at this point is transmitted Love waves.

![Figure 4.10 Ray paths associated with Event 89.](image)
The waveforms of the transmitted signals are presented in Figure 4.10, where part (a) is the original record and part (b) is the original signal processed by a 200 – 600 band pass filter. The trend of the Love waves is quite evident even for the original one. For the convenience of discussion, the two bands were marked in part (b). The first was the S-waves transmitted in coal. The width of this band is nearly constant. The second band delineates the approximate location of the Love waves with the Airy-phase at the center. This band clearly shows a dispersion effect: the band is getting wider as the distance increases. The figure also shows that the Love waves are quite resilient. Compared to the body waves that arrive earlier, these Love waves have relatively high amplitude and a much longer duration. A close-up of these Love waves also shows that even their appearance is very similar (Figure 4.11).

![Figure 4.11](image)

**Figure 4.11** Love waves from the transmitted signals associated with Event 89.

**a. Original recorded waveform**
b. Original recorded waveform processed with a 200 – 600 Hz band pass.

Figure 4.12 (continued).

Figure 4.13 A close-up view of Love waves shown in Figure 4.10 part b.
4.4.2 Characteristics of Dispersion Curves

Theoretically, Love waves may travel with a wide range of velocities, from a low value somewhere around 70% of the S-wave velocity of the seam, to an upper limit equal to the S-wave velocity of the country rock (Arnetzl and Klinge, 1982). For the ISS-based void detection, one is interested in the dispersion curve with the velocity near and below the seam S-wave velocity. The velocities above the S-wave velocity of the seam are highly unstable and have no practical application in the ISS-based void detection technique. Because of this, the dispersion curve for the Harmony Mine site was restricted to a section where the velocities are near and lower than the S-wave velocity of the seam. Such an example is given in Figure 4.12.

The dispersion curve in Figure 4.12 (c) is representative of the Harmony site. The original waveform and the zoomed Love wave portion are given in Figure 4.12 (a) and 4.12(b), respectively. The shape of the Love wave shown in Figure 4.12 (b) is typical for the Harmony site. It is also typical from a theoretical point of view, namely: a relatively high-amplitude, high-frequency component preceded by a series of low-amplitude, low-frequency components. The former is known as the Airy-phase.

In general, the Love waves observed from the transmission surveys had a frequency range of 300 – 900 Hz with a velocity range of 1372 – 914 m/s (4500 – 3000 ft/s). The typical frequency range for the Airy-phase was 400 – 600 Hz. The velocity for the Airy-phase, however, was quite stable, with a typical value of 975 m/s (3200 ft/s).
Figure 4. A typical transmission signal, Love wave component and associated dispersion curve observed at Harmony Mine Site II.
Chapter 5

WAVELET ANALYSIS

5.1 Introduction:

It is known that in-seam seismic signals are non-stationary in their frequency and amplitude statistics. ISS signals usually vary in both amplitude and frequency over long periods of time. Ideally, for the ISS signal analysis, one would like to separate short period oscillations from long period ones. One solution would be to use a Short Time Fourier Transform (STFT), which was briefly introduced earlier in section 4.3.4. The STFT uses a window with a fixed size, slides it along in time, and computes the Fourier transform each time, using only the data within the window. The main problem with this technique is the inconsistent treatment of different frequencies. The frequency localization may be lost for low frequency signals, as there are few oscillations within the window and for high frequency signals as there are too many oscillations within the window.

Wavelet analysis is used to solve these problems by decomposing a signal into time and frequency space simultaneously. With wavelet analysis, one can get information on the frequency of a signal, and how this frequency varies with time. Also, the wavelet transform is more precise than the STFT to “zoom in” on phenomena with a very short time period and high frequencies, such as transient signals. The information of time-frequency localization provided by the wavelet transform helps with analyzing the dispersion characteristics of the Love waves and the identification of the reflection signal.
In this chapter, the use of wavelet analysis for ISS signal processing will be discussed. Readers may refer to section 2.4.3 for some background discussion.

5.2 Wavelet Functions and Wavelet Coefficients

Two functions play a primary role in wavelet analysis, the scaling function $\phi$ and the wavelet function $\psi$. Because of their close relationship and ability to generate a family of wavelets, $\phi$ is sometimes called the ‘father wavelet’ and the $\psi$, the ‘mother wavelet.’ With the rapid development of wavelet theory and its application, more than ten types of wavelets have been constructed, and software packages are available for the purpose of analysis. The one utilized for this current research is Wavelet Toolbox, a standard tool developed by MathWorks, Inc. Wavelet Toolbox provides wavelet-based algorithms for the analysis, synthesis, denoising, and compression of signals and images. Some typical wavelets in the toolbox are shown in Figure 5.1.

![Wavelet Functions and Coefficients](image-url)
Based on the author’s experience, two kinds of wavelets were selected for the analysis of the ISS data, the Daubechies wavelet and the Gabor wavelet.

5.2.1 The Daubechies Wavelets

The simplest and earliest wavelet developed was the Haar wavelet, and all the discussion of wavelets originated with it (Boggess, 2001). The Haar wavelet and scaling function are defined by Equations 5.1 and 5.2. The graph of these two functions is given in Figure 5.2 (a). One can see that Haar wavelets are particularly simple. Figure 5.2 (b) illustrates the general application of the Haar wavelet for the approximation of a signal. With this example, we see that a signal can be approximately represented as a sum of a finite number of steps, which are the combination of wavelets at different scales.

\[
\psi(x) = \begin{cases} 
1, & 0 < x < 1/2 \\
-1, & 1/2 \leq x < 1 \\
0, & \text{otherwise}
\end{cases} \quad (5.1)
\]
\[ \phi(x) = \begin{cases} 1, & 0 \leq x < 1 \\ 0, & \text{otherwise} \end{cases} \] (5.2)

Figure 5.2 Graph of the Haar functions and an example of the application of the Haar wavelets.

(a) The Haar wavelet and scaling functions. (b) Approximation of a signal by the Haar functions.

The Haar wavelet is a special case of the Daubechies wavelet family (db1). Daubechies wavelets are regarded as the cornerstone of wavelet development. Named after Ingrid Daubechies, the Daubechies wavelets are a family of orthogonal wavelets defining a discrete wavelet transform (Daubechies, 1992). With each wavelet type of this class, there is a scaling function (the father wavelet) which generates an orthogonal multi-resolution analysis. Figure 5.3 shows two other Daubechies wavelets, numbered db4 and db10. The Daubechies wavelet was used quite often in signal decomposition and reconstruction which will be discussed in the next sections.
5.2.2 Gabor Wavelets

Besides Daubechies wavelets, another wavelet, called Gabor wavelet was used and found successful in the current study. The mother wavelet is given as

\[
\psi(t) = \pi^{-1/4} \left( \frac{\omega_p}{\gamma} \right)^{1/2} \exp\left[ - \frac{t^2}{2} \left( \frac{\omega_p}{\gamma} \right)^2 + i \omega_p t \right]
\]  

where \( \omega_p \) is the center frequency and \( \gamma \) is a constant to satisfy the orthonormality condition. The shape of the Gabor wavelet is shown as Figure 5.4.
According to Laurent Demanet and Pierre Vandergheynst, there are two advantages to using the Gabor wavelet. First, it is more adaptive to the fine local geometry of complex datasets. Second, the rotation parameter used by the wavelet provides the extra degree of freedom. This feature is very useful when one wants to detect objects in very noisy environments (Demanet and Vandergheynst, 2003).

5.2.3 Wavelet Coefficients

Wavelet transform, as illustrated with Figure 5.2 (b), is the sum of a signal multiplied by the scaled, shifted versions of a wavelet. A more general illustration of the process of wavelet transform is shown in Figure 5.5. This process produces wavelet coefficients that are a function of the scale and position. There are four major steps. Step 1 is to compare a wavelet with a segment of the original signal. A coefficient number is then calculated which represents the correlation or similarity between the wavelet and this segment of the signal. The value of the position ($t_1$) and scale ($a_1$) of the wavelet is saved. Step 2 is to shift the wavelet along the time axis and repeat step 1 for the whole signal. Step 3 is to scale (stretch or compress) the wavelet and repeats steps 1 and 2. Step 4 is to repeat steps 1 through 3 for all scales. After this procedure, a matrix of the wavelet coefficient $C(t_i, a_j)$ at different sections of the signal, at different scales, will be produced.
Figure 5.5 Schematic processing sequence of the generation of wavelet coefficients.

Now one can make a plot on which the $x$-axis represents a position along the signal (time), the $y$-axis represents scale, and the color at each $x$-$y$ point represents the magnitude of the wavelet coefficient. Figure 5.6 is the coefficient plot of a signal from Event 89 Channel 3. The wavelet applied here is the Daubechies 10 (db10).
Figure 5.6 A plot of Daubechies wavelet transform showing the time-scale of a signal and the magnitude of the wavelet coefficients.

5.3 Wavelet Analysis

Wavelet analysis was found to be an efficient tool in analyzing the ISS data from the Harmony Mine. The application can be divided into four categories, namely: time-frequency analysis for signal identification, dispersion analysis for velocity determination, wavelet decomposition and reconstruction for channel waves, analysis and enhancement of reflection signals for void mapping.

5.3.1 Time-Frequency Analysis

A signal can be viewed in the time domain or the frequency domain. Seismic signals in the time domain show the sequence of different components and their amplitude, whereas signals in the frequency domain show the basic frequency spectrum property. For ISS
signals, one wants to know both the time and the frequency information, and to analyze
the signals using both time and frequency simultaneously, if possible. This time-
frequency analysis is realized by wavelet transform.

The data associated with the ISS-based void are complicated in nature. Signals from the
roof and floor, and signals from the coal seam were superimposed. Problems exist as to
how to differentiate channel waves from refracted S- waves. It is also very challenging to
detect reflection signals as they are often hampered by background noises and long-
lasting transmission waves. In order to solve these problems, it is more efficient if the
signals can be viewed and analyzed simultaneously in both the time and frequency
domains by using wavelet transform. Such an example is given in Figure 5.7. Part a is the
original signal; part b is the plot of the wavelet transform coefficient with Gabor wavelets;
part c is a 3D display of the plot.

In this example, there are three isolated ‘areas’ of signals: refracted P- waves, refracted S-
waves, and transmitted channel waves, which are separated by both time and frequency.
Figure 5. 7 Wavelet transform for Event 43 Ch3. Plot (a) shows the original waveform, Plot (b) shows a 2D color contour of the wavelet coefficient, Plot (c) shows a 3D color contour of the wavelet coefficient.
There are also strong Love waves at the end of the waveform, and the peak one is the Airy-phase. The 3D displays of the wavelet transform clearly illustrate the relations among refracted P- and S-waves and Love waves simultaneously by time, frequency, and wavelet coefficient. The 3D image of the signal in terms of these three factors is very helpful to recognize the pattern of the seismic signals. The wavelet transform provides a convenient tool to identify the arrival time of seismic signals by examining their time-related frequency characteristics, and make it an ideal method to determine different seismic signals.

A time-frequency analysis has also proven to be a very efficient means for a whole event analysis. Recall Event H2E89 shown in Figure 4.11. Wavelet transform was implemented for the six channels of this event as shown in Figure 5.8. The time-frequency analysis provides an insight investigation of the whole event. The trend of the Love wave is very clear after the wavelet transform. Three bands were marked in Figure 5.8. The first two are S-waves transmitted in country rock and a coal seam. The width of these bands is nearly constant. The third band delineates the approximate location of Love waves with the Airy-phase at the center. This band clearly shows a dispersion effect: the band is getting wider as the distance increases. The wavelet contour (coefficient) demonstrated that these Love waves have a relatively higher amplitude and longer duration. The Airy-phase of channel waves, as indicated with the red dash lines, formed a clear trend with a consistent frequency around 500 Hz.
Figure 5.8 Time-frequency analysis for Event H2E89. There are two trends of non-dispersive body waves and one trend of dispersive Love waves. Love waves are consistent with frequency at 500 Hz.

5.3.2 Dispersion Analysis

Chapter 4 contained a brief discussion of the dispersion character of Love waves. The extraction of dispersion curves from transmission surveys can be conducted in different ways. The calculation in Chapter 4 was based on the travel distance and the arrival time reading of the peak and trough time of the waveform. This method is easy to use. One problem that may arise is that if signals with a high and low frequency are superimposed,
the peak and trough time reading will contain information on more than one signal, and thus the dispersion curve will not be correct. A solution to this problem is to use digital filters to process the signal before the dispersion analysis, however, experience is needed in order to select a proper bandpass filter. Poor filters will cause a phase shift and thus affect the accuracy of the velocity.

A multiple filter technique (MFT) introduced by Dziewonski, Block, and Landisman (1969) is a frequently used method for the determination of velocity and the dispersion of seismic signals. The flow chart in Figure 5.9 gives an overview of the processing steps. This method involved Fourier transform, inverse Fourier transform, and windowed spectrum calculations. Manual selection of the center frequency and group arrival time was necessary. The procedure described in points 6 through 9 must be repeated for each center frequency.

Figure 5.9 Flow chart of the multiple filtering analysis process (after Dziewonski et al., 1969).
With MFT, the amplitude and phase of a signal were filtered by an array of narrow bandpass filters to measure the velocity and dispersion character. An example of multiple filter analysis of surface waves is shown in Figure 5.10. The right side of the figure is the original signal, and the contour shows the relationship between the period and the velocity of the signals.

Figure 5. 10 An example of multiple filter analysis of surface waves (after Dziewonski et al., 1969).

A multiple bandpass filter with 150 Hz intervals was applied to a transmission signal from Harmony Mine Site II, as shown in Figure 5.11. The signals after filtering were normalized with the same scales. Two dash lines showed the approximate group arrivals of the S-wave and the Love waves. However, the manual selection of the center frequency and the group arrival time reading turned out to be very difficult.
In the current research, a wavelet transform based dispersion analysis (WTDA) method was introduced and developed. The process of this method is explained with the help of Figure 5.12. In this figure, part a is the original waveform. The first step of the method is the wavelet transform by applying the Gabor wavelet to the ISS signal. The result of this transformation is the wavelet coefficient, a matrix with time and frequency values as rows and columns. The plot of the wavelet coefficient is shown in part b of the figure. The next step is to convert the time values into associated velocity values, which are the ratio of the travel distance and the time values. Then the relationship between the velocity and the frequency (dispersion curves) can be plotted. The result is shown in part c, and a expanded view of it is given in Figure 5.13.

Figure 5.11 A transmission signal filtered by multiple bandpass filters with an interval of 150 Hz.
The contour in Figure 5.13 clearly shows that there are three major wave groups. The shape of the contour shows that the two top ones are non-dispersive body waves and the bottom one is dispersive Love waves. The Airy-phase of the channel wave has the highest amplitude. The dispersion curve shows that the Airy-phase of the Love waves has a velocity of 3200 ft/s at a frequency around 500 Hz.
Figure 5.13 An expanded view of a dispersion curve in Figure 5.12 part c. There are two non-dispersive body wave components and one dispersive channel wave with strong Airy-phase.

Compared with the multiple filter method, the WTDA does not need to determine the group arrival time and center frequency of a bandpass filter by hand, since the unique function of wavelet transform that can track and save the time and frequency information simultaneously. The computational scheme of dispersion analysis with WTDA can be easily summarized with the follow flow chart. The program code can be found at Appendix E.
1. Wavelet Transform
\[ f(t) \rightarrow W(t, f) \]

2. Velocity Calculation
\[ v = \frac{Dist}{t} \]

3. Dispersion Curve Plot
\[ WTDA(v, f) \]

Figure 5.14 Flow chart of wavelet transform-based dispersion analysis.

Another example using WTDA is given as Figure 5.15. Part \( a \) is the original waveform of Event 43 Channel 3. Part \( b \) is the wavelet coefficient. Part \( c \) is the dispersion curves. An expanded view is given in Figure 5.16.

Figure 5.15 Wavelet transform based dispersion analysis for Event 43 Ch3. (a) original signal, (b) wavelet transform, and (c) dispersion curves.
Similarly to Figure 5.14, Figure 5.16 shows that there are three major wave groups. The two top ones are the non-dispersive body waves and the bottom ones are the dispersive Love waves. It is important to note that the dispersion curves of body waves are totally different from those in Figure 5.14, but the shapes of the dispersion curves of the Love waves are identical in these two figures. The dispersion curve in Figure 5.16 shows that the Airy-phase of Love waves has a velocity of 975 m/s (3200 ft/s) at a frequency around 440 Hz. This indicates that the velocity-frequency relationship of the Love waves is very consistent, which is critical for the ISS-based mine void detection technique.

Figure 5.16 A expanded view of the dispersion curve in Figure 5.15 (c). There are two non-dispersive body wave components and one dispersive channel wave with a strong Airy-phase.
5.3.3 Wavelet Decomposition

Arrival time reading is important for the accuracy of void mapping. Theoretically, the wavelet transform has a good time resolution for higher frequencies and a good frequency resolution for low frequencies (Chakraborty and Okaya, 1995). The in-seam seismic signals at Harmony Mine are typically band-limited within a frequency range from 200 Hz to 1000 Hz. This implies that the ISS signals are rich in intermediate to high frequencies. In other words, a good time resolution can be achieved by wavelet transform for ISS signals. Wavelet decomposition therefore matches this requirement.

An important application of wavelet transform is signal decomposition, which considers that each signal is composed of two parts, approximate and detail, and each part is a new signal and is composed of two parts. Therefore, a complex signal can be decomposed many times, say \( n \), with \( 2^n \) components at the \( n \)th layer. The number of times for decomposition depends on the characteristics of the signal as well as the required resolution.

Mathematical expression of this decomposition process is given by the following equation:

\[
s = a_1 + d_1 = a_2 + d_2 + d_1 = a_3 + d_3 + d_2 + d_1 = \cdots = a_6 + d_6 + d_5 + d_4 + d_3 + d_2 + d_1
\]

(5.1)

where \( s \) is the original signal, ‘\( a \)’ is approximate and ‘\( d \)’ is detail. Unlike conventional techniques, wavelet decomposition produces a family of hierarchically organized decompositions. The selection of a suitable level for the hierarchy will depend on the signal and experience.
Figure 5.17 is an example of wavelet decomposition, where the Daubechies wavelet ($db6$) is used to decompose Ch2 of Event 89. The original signal mainly consisted of three types of signals: background noises, refracted S-waves, and Love waves. With wavelet decomposition, those signals are separated: $d1$ is dominated by noises, $d5$ and $d6$ show the low frequency refracted body waves, and $d3$ and $d4$ are dominated by the high amplitude Love waves, especially the Airy-phase. (See Appendix D for programming code.)

This technique is extremely useful for analyzing reflection data, which are often very weak, but relatively stable in frequency. A detailed discussion on this issue will be given in the next section.
Figure 5.17 Wavelet decomposition of Event H2E89 Ch3 showing that detail 4 (d4) has good representation of channel waves.

Another example illustrated in Figure 5.18 shown that detail 5 (d5) also has good representation of channel wave. After channel-by-channel analysis, d4 and d5 proved to have the best details for the representation of the original channel waves.
Figure 5.18 Wavelet decomposition of Event H2E89 Ch13 showing that both detail 4 (d4) and detail 5 (d5) have good representation of the channel waves.

In the case of the signal in Figure 5.18, after wavelet decomposition, the next step is to reconstruct the signals by selecting the best details and ‘muting’ the noisy details. This technique is also very useful to analyze reflection signals, because the signal-to-noise-ratio of a reflection signal is relatively small compared with that of transmission signals.

We have demonstrated that d4 and d5 of the Daubechies wavelet are a good match with channel waves. The following is the application of wavelet decomposition for a transmission event. The original waveform in Figure 5.19 a shows signals with various
but continuous frequencies. With wavelet decomposition, two clear trends of Love waves were turned out, and the arrival time can be easily and more accurately read than the original one (Figure 5.19 b. The velocities of these two trends of Love waves were calculated as 975 m/s (3200 ft/s) and 853 m/s (2800 ft/s), respectively.

![Figure 5.19](image-url)  
**Figure 5.19** Original seismogram of Event 43 and wavelet decomposition (detail 4 of db10) shown clear and sharp trend of channel waves.
5.3.4 Wavelet Analysis for Reflection Signal Enhancement

One big challenge for ISS signal analysis is to detect reflection signals, because these signals are relatively weak compared to direct waves. A typical method to enhance the reflection signals is to mute the transmission signals and amplify the reflection ones. A case study is given in the following example.

Figure 5.19 shows Event 89 of a reflection test. The waveform is dominated by the refracted body waves and transmitted channel waves. The original waveform of this event, as shown in part a, displays strong channel waves. After wavelet decomposition, the waveform of \( d4 \) shows even clearer trends of refracted P- and S- waves and transmitted Love waves as seen in part b. However, the reflection signals are barely visible, as these transmission signals dominant the amplitude.

Figure 5.20 shows the reflection signals after muting the transmission signals. Part a is the original signal with very high background noises. As explained in Figure 5.18, wavelet details \( d4 \) and \( d5 \) of \( db10 \) have the best representation of the channel waves. Because the time-frequency character of the channel wave has proven to be consistent, the same procedure of wavelet analysis was applied to the reflection signals. Part b is the waveform after the wavelet decomposition and reconstruction with these details. A clear trend in reflected Love waves emerged after wavelet analysis.

This example shows that reflection signals can be enhanced with wavelet decomposition and reconstruction to remove the noises and amplify the reflection channel waves.
Figure 5. 19 Original seismogram of Event 89 wavelet decomposition (detail 4 of db10) shows strong and sharp trend of transmitted Love waves.
Figure 5. 20 Original reflection signals and wavelet decomposition and reconstruction show a clear trend of reflection Love waves.
5.4 Summary and Discussion

Wavelet analysis can study a signal in both time and frequency domains simultaneously. This unique capacity of wavelet analysis provides an insight into the signal. Wavelet transform generates much more information than a conventional Fourier transform, by tracking the time and frequency simultaneously. The wavelet transform is also more accurate than the STFT for transient signals with a very short time period and high frequencies.

Dispersion analysis is one of the most important aspects of ISS signal analysis. There are, however, drawbacks with the manual reading of peak and trough arrival time. A multiple filter technique is a commonly used method for this analysis, but the procedure is tedious and the selection of frequency and arrival time is difficult. An advanced method proposed and developed in the current research is called wavelet transform-based dispersion analysis (WTDA), which has proven to be a very efficient and fast method for dispersion analysis.

Wavelet decomposition and reconstruction appears to be a very useful tool for separating Love waves from noises. It is also valuable for detecting reflection signals whose signal-to-noise-ratio is relatively very small. Reflection signals can be enhanced after wavelet decomposition and reconstruction.
6.1 Introduction

The final stage of the ISS-based mine void detection is to map the void using seismic reflection data. In this chapter, reflection surveys and data will be introduced, followed by the steps to identify reflection signals with case studies. Based on actual reflection events, the author proved that the ISS technique is not only theoretically sound, but also practically feasible in hard coal mines. Void mapping at the end is the final step to validate the reflection study and the overall ISS void detection technique.

6.2 Reflection Survey

Harmony Mine Site II was utilized for both transmission and reflection surveys. The test site with the experiment setup is shown in Figure 6.1, where the sensor holes were numbered from S1 to S15, the blasting holes for transmission surveys were numbered from T1 to T25, and the blasting holes for reflection surveys were numbered from R1 to R16.

Ten reflection surveys (blasting events) were carried out at Site II. The seismic sources used for the surveys were 125 gram explosives and caps. The explosives used and the associated event numbers for these surveys are listed in Table 6.1. Among these ten surveys, six have both clear signals and triggering times. These events are 53, 58, 72, 85, 89, and 97.
Figure 6.1 Mine map and experimental setup at Harmony Mine Site II.

<table>
<thead>
<tr>
<th>Hole #</th>
<th>Explosive (g)</th>
<th>Event #</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>R16</td>
<td>125</td>
<td>53</td>
<td>Good</td>
</tr>
<tr>
<td>R13</td>
<td>125</td>
<td>58</td>
<td>Good</td>
</tr>
<tr>
<td>R11</td>
<td>125</td>
<td>72</td>
<td>Good</td>
</tr>
<tr>
<td>R9</td>
<td>125</td>
<td>85</td>
<td>Good</td>
</tr>
<tr>
<td>R8</td>
<td>125</td>
<td>89</td>
<td>Good</td>
</tr>
<tr>
<td>R7</td>
<td>125</td>
<td>97</td>
<td>Good</td>
</tr>
<tr>
<td>R5</td>
<td>Cap</td>
<td>108</td>
<td>Waveform Saturated</td>
</tr>
<tr>
<td>R4</td>
<td>Cap</td>
<td>114</td>
<td>Waveform Saturated</td>
</tr>
<tr>
<td>R2</td>
<td>Cap</td>
<td>125</td>
<td>Waveform Saturated</td>
</tr>
<tr>
<td>R1</td>
<td>Cap</td>
<td>129</td>
<td>Waveform Saturated</td>
</tr>
</tbody>
</table>
6.3 Reflection Signals

As an example of reflection surveys, the original and reflection signals of event 89 are presented in Figure 6.2.

Figure 6.2 Waveform of Event 89. (1) transmission signals, (2) reflection signals, and (3) noises.
On the left side is the original waveform, which showed strong transmission signals. The reflected signals could not be seen because the waveform was dominated by the transmission signals. The waveform on the right side was processed where the reflection signals were enhanced by muting the transmission signals.

Compared with transmission signals, the reflection signals were very weak. There are several factors contributing to weak reflection signals. The first is due to the effect of geometric spreading. When waves propagate outward from the source, their amplitudes decay with the distance because the energy is spread out over an increasing surface area. For geotechnical applications, the decay of amplitude due to geometric spreading is generally considered to be the spherical type, which is described by $A = A_0 / r$, where $A_0$ is the stress wave amplitude at the source, and $A$ is the amplitude at a distance $r$ from the source. For an in-seam seismic survey, the energy is trapped in the seam and spreads two-dimensionally. The energy decay due to geometric spreading is described by $A = A_0 / r^{1/2}$.

Because of its predominant effect on signal strength, geometric spreading is one of the most important factors affecting the magnitude of seismic events.

The second factor is attenuation, which refers to the phenomenon of the energy dissipation caused by internal friction, scattering and mode conversion. Because of its complex process and site dependent nature, the evaluation of the attenuation effect for a particular site relies on the field measurement. The overall attenuation effect can be measured by an equivalent attenuation factor ($\alpha_e$) (Hardy, 2003), namely,

$$\alpha_e = \frac{20}{d} \log\frac{A_1}{A_2}$$

(6.1)
where $\alpha_e$ is the equivalent attenuation factor, $d$ is the distance between sensors, and $A_1$ and $A_2$ are the peak signal amplitudes at sensor 1 and 2. Attenuation is strongly related to signal frequencies. Figure 6.3 shows attenuation ($\alpha_e$) as a function of frequency for various materials.

Thirdly, reflection signals from an interface can vary from strong to weak, depending on the roughness of the interface. If the scattering of waves at the interface is severe, the event may not be detectable by some sensors or even an entire array. The effect of scattering or diffusion is explained in Figure 6.4. Because the surface of the mine void is not smooth, the reflected seismic signals are broken up into many seismic beams that are reflected in all directions.
It is easy to understand from Figure 6.4 that signals with shorter wavelengths are more vulnerable to the scattering problem than those with longer wavelengths. In other words, low frequency signals are more easily reflected. The trade off is that high frequency signals have a higher resolution.

Noise is one of the major issues that needs be addressed carefully during ISS field tests. There are three main sources of noise, including background noise caused by mining machinery, mine ventilation and human activities, electric noise (60 Hz and multiples) from the data acquisition system, and air shock waves due to blasting. Every effort was made to minimize the background noise, including conducting the test during the non-production period, paying attention to grounding, using sound proof materials to seal sensor holes, and using a suitable amount of explosives.

The weakness of reflection signals can be quantitatively studied in terms of signal-to-noise ratio (SNR), which is defined by the following two equations:
where $P$ is the average power (the square of the amplitude) and $A$ is the root mean square (RMS) amplitude of the signals.

As a comparison, the SNRs for both transmission and reflection signals are listed in Table 6.2. To simplify the problem, the RMS amplitude was replaced by a maximum amplitude. On average, the SNR is 8926 and 4.4 for transmission and reflection signals, respectively. The energy of the reflection signals was about 2000 times weaker than that of the transmission signals for this particular event.

Table 6.2 Signal-to–Noise-Ratio of transmission and reflection signals*

<table>
<thead>
<tr>
<th>Ch. No.</th>
<th>A (N)</th>
<th>A (T)</th>
<th>A (R)</th>
<th>A (T/N)</th>
<th>A (R/N)</th>
<th>SNR (T/N)</th>
<th>SNR (R/N)</th>
<th>SNR (T/N)(dB)</th>
<th>SNR (R/N)(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch2</td>
<td>0.006</td>
<td>0.75</td>
<td>0.0071</td>
<td>125.0</td>
<td>1.2</td>
<td>15625.0</td>
<td>1.4</td>
<td>41.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Ch3</td>
<td>0.0092</td>
<td>1.8</td>
<td>0.018</td>
<td>195.7</td>
<td>2.0</td>
<td>38279.8</td>
<td>3.8</td>
<td>45.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Ch4</td>
<td>0.008</td>
<td>0.1</td>
<td>0.008</td>
<td>12.5</td>
<td>1.0</td>
<td>156.3</td>
<td>1.0</td>
<td>21.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Ch5</td>
<td>0.0053</td>
<td>0.8</td>
<td>0.013</td>
<td>150.9</td>
<td>2.5</td>
<td>22783.9</td>
<td>6.0</td>
<td>43.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Ch7</td>
<td>0.0089</td>
<td>0.88</td>
<td>0.019</td>
<td>98.9</td>
<td>2.1</td>
<td>9776.5</td>
<td>4.6</td>
<td>39.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Ch8</td>
<td>0.006</td>
<td>0.57</td>
<td>0.01</td>
<td>95.0</td>
<td>1.7</td>
<td>9025.0</td>
<td>2.8</td>
<td>39.6</td>
<td>4.4</td>
</tr>
<tr>
<td>Ch9</td>
<td>0.0042</td>
<td>0.33</td>
<td>0.012</td>
<td>78.6</td>
<td>2.9</td>
<td>6173.5</td>
<td>8.2</td>
<td>37.9</td>
<td>9.1</td>
</tr>
<tr>
<td>Ch10</td>
<td>0.0043</td>
<td>0.3</td>
<td>0.0071</td>
<td>69.8</td>
<td>1.7</td>
<td>4867.5</td>
<td>2.7</td>
<td>36.9</td>
<td>4.4</td>
</tr>
<tr>
<td>Ch11</td>
<td>0.0046</td>
<td>0.43</td>
<td>0.014</td>
<td>93.5</td>
<td>3.0</td>
<td>8738.2</td>
<td>9.3</td>
<td>39.4</td>
<td>9.7</td>
</tr>
<tr>
<td>Ch12</td>
<td>0.015</td>
<td>0.22</td>
<td>0.015</td>
<td>14.7</td>
<td>1.0</td>
<td>215.1</td>
<td>1.0</td>
<td>23.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Ch13</td>
<td>0.0067</td>
<td>0.99</td>
<td>0.03</td>
<td>147.8</td>
<td>4.5</td>
<td>21833.4</td>
<td>20.0</td>
<td>43.4</td>
<td>13.0</td>
</tr>
<tr>
<td>Ch14</td>
<td>0.022</td>
<td>0.96</td>
<td>0.035</td>
<td>43.6</td>
<td>1.6</td>
<td>1904.1</td>
<td>2.5</td>
<td>32.8</td>
<td>4.0</td>
</tr>
<tr>
<td>Ch15</td>
<td>0.0043</td>
<td>0.44</td>
<td>0.01</td>
<td>102.3</td>
<td>2.3</td>
<td>10470.5</td>
<td>5.4</td>
<td>40.2</td>
<td>7.3</td>
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<tr>
<td>Average</td>
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<td></td>
<td></td>
<td>94.5</td>
<td>2.1</td>
<td>8925.6</td>
<td>4.4</td>
<td>37.4</td>
<td>5.7</td>
</tr>
</tbody>
</table>

* Abbreviations: A: amplitude, N: noise, T: transmission signals, R: reflection signals, SNR: signal to noise ratio, dB: decibel.
6.4 General Steps to Identify Reflection Signals

Because of the very weak appearance of the reflection signals, the key issue of the data analysis is identifying these weak signals. In general, it is a three-stage process. The first is a careful visual inspection to search for evidence of reflection signals. Next, Fourier transform and digital filtering are used to separate Love waves from noises. The final stage is to further enhance the appearance of the reflection signals. A principal tool used at this stage is wavelet analysis.

6.4.1 Data Organization and Visual Inspection

The first step of the data analysis is data organization. In this research, MatLAB was utilized as the basic data processing platform due to its rich functions of signal analysis and graphic processing. Seismic data were first converted into digital ‘txt’ format, which could be further processed with MatLAB. Events and channels with recording problems were removed. For a better view and presentation, the seismograph might be rotated. The signal amplitude may vary significantly from channel to channel for a variety of reasons. For the convenience of data analysis, it is often necessary to normalize the signals on all channels by setting their maximum amplitude to the same level. Such an example is shown in Figure 6.5, where part $a$ is the original waveform and part $b$ is the normalized one. The trend in the reflection of Love waves cannot be detected in part $a$, but can be roughly seen in Part $(b)$. 
6.4.2 Fourier Transform and Bandpass Filtering

Digital filters were designed to remove the signals with unwanted frequencies. It is important, however, to know the potential negative effect of filtering, such as phase shifting and inducing additional frequency components. Therefore, one has to be cautious on filter selection and filter design. During this research, several types of filters with different bandwidth were tested for transmission signals, including Butterworth filters, Bessel filters, Elliptic filters, Chebyshev filters and others. As a result of these tests, the Chebyshev digital filters were chosen. The magnitude response of the bandpass filter using the Chebyshev 1 digital filter is shown in Figure 6.6.
Figure 6.6 Magnitude response of the bandpass filter using the Chebyshev 1 digital filter (200–600 Hz) with steep roll-off and small ripple.

After the most suitable type of filters was determined, the next question was what was the most suitable frequency range to use. Based on the analysis of the transmission data, it was determined that a 200 – 600 Hz band pass filter was most suitable for the Harmony site. Figure 6.7 is an example where this filter was applied to the signals shown in Figure 6.5. It is evident that the trend becomes much clearer after applying this bandpass filter.
Figure 6.7 Signals processed by a 200–600 Hz bandpass filter.

6.4.3 Programmed Gain Control

Another approach to enhance the reflection signals is to bring up weak signals with gain control. With this approach, a time-variant scaling function is applied to the signals based on a desired criterion. Such an example is given in Figure 6.8. In this figure, part $a$ is the original trace of channel 8 of Event 89, part $b$ shows the gain function $g(t)$, and part $c$ is the resulting waveform which is obtained by multiplying the original signal (part $a$) and by the gain function (part $b$).
Figure 6.8 Gain is a time-variant scaling defined by a function $g(t)$. Gain function is defined as the time samples that are the center of time gates along the trace (b). The output (c) is found by multiplying of original signal (a) by the gain function (b).

It was observed from Figure 6.8 (c) that there are only high and low frequency noises after 0.2 second, where a very high gain has to apply to this segment of signals as shown in part (b). A zoom-in view of the seismic signal before 0.2 second is shown in Figure 6.9. The amplitudes of the signal decay very fast after the transmission signals. For gain control, the trace is cut into windows/gates at 20 ms intervals. The amplitude is then computed as a root-mean-square or RMS amplitude. The programmed gain control (PGC) applied is calculated as the inverse of the original trace envelope. The last part of the figure shows that reflected signals emerged around the anticipated arrival time.
After the gain control process, “wiggle plotting”, a typical method of seismic signal analysis, may be used. With this method, the positive part of a trace is filled with black to highlight the trend of the correlated signals. Figure 6.10 is the wiggle display of the original waveform of Event 89. The wiggle display shows clear trends in S-waves and direct channel waves.

Figure 6.9 A close up view of Figure 6.8 showing transmitted and reflected Love waves after gain application.
Figure 6. 10 Wiggle display of original waveform of Event 89 showing strong direct waves, including transmitted S-waves refracted from the roof and floor, direct S-waves from the coal seam, and Love waves from the coal seam.

With gain control as shown in Figure 6.9 part c, the original character of the seismic waves was mostly lost. One hopes that there is a tradeoff so that the reflection signals can
be enhanced. A close up view of the anticipated reflection waves is displayed in Figure 6.11. The waveforms are complex and it is difficult to find clues for the reflection signals.

![Waveform after gain control at anticipated reflection time.](image)

Figure 6.11 Waveform after gain control at anticipated reflection time.

Now, the wiggle display is applied to the waveform after gain control. Figure 6.12 shows the results where there is a clear and continuous trend of reflection signals. The trend is also matched with those found with the bandpass filter and wavelet analysis.
Figure 6. 12 A continues and strong trend of reflection Love waves with wiggle display after gain control.

6.4.4 Wavelet Analysis

The ability of the time-frequency localization by wavelet analysis makes it particularly useful for processing the ISS data. Readers can refer to Chapter 5 for a detailed discussion of wavelet analysis. As an example, the trend shown in Figure 6.7 can be further enhanced by wavelet analysis. Figure 6.13 is the result of wavelet decomposition with the Daubechies 10 wavelet.
6.5 Void Mapping

Delineating the mine void location with reflection data is the final step of the ISS-based void detection technique. A method that is inherently compatible with the conditions associated with the ISS-based void detection is the elliptical mapping method (EMM). With this method, all travel time information of reflected signals is represented by ellipses, and the void is delineated by the common tangent line of these ellipses. In addition to its flexibility for accommodating the testing conditions typically encountered with the ISS-based void detection, the method is also robust for data processing and offers a number of unique advantages, which include simultaneously using different types of reflected signals, simultaneously using reflected signals from different surveys, and

Figure 6. 2 Signals processed by a wavelet transform.
handling irregular void boundaries. Finally, the method is simple and straightforward, avoiding many data manipulating procedures which may be required otherwise. Details of this method are detailed in the final project report of phase I (Ge, 2006).

6.5.1 Concept of Elliptical Mapping Method

An ellipse is a trace such that the sum of the distances from any point of the trace to the two points is a constant. These two points, which are denoted by F1 and F2 in Figure 6.14 (a), are called the foci of the ellipse.

![Ellipse and its parameters](after Ge, 2006)

When the foci are located on the x-axis and are symmetrical to the y-axis, an ellipse has a simple mathematical expression:

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1
\]  

(6.1)

The geometrical meanings of parameters \( a \) and \( b \) are given in Figure 6.14 (b), where the line segment that joins the vertices (-\( a \), 0) and (\( a \), 0) is called the major axis, and the line segment that joins the vertices (0, -\( b \)) and (0, \( b \)) is called the minor axis. The length of the major axis is given by 2\( a \) and the length of the minor axis is given by 2\( b \).
It is known from Figure 6.15 that the parameters of $a$, $b$ and $c$ satisfy the following equation:

$$b^2 + c^2 = a^2$$  \hspace{1cm} (6.2)

The reflection survey relies on two pieces of information: locations of seismic sources and receivers, and signal travel distances between sources and receivers. If one considers a source and a receiver as the foci and use the signal travel distance as the sum of the distances, it is immediately known that an ellipse is uniquely defined and that the reflection point must be on the ellipse.

According to analytical geometry, the ellipse not only defines the trace of the potential reflection point, but also the direction of the reflector, which is the tangent line of that point. This reflecting property of the ellipse is critical for void mapping. Based on this property, the void can be delineated by a common tangent line, which is illustrated in Figure 6.15.

![Figure 6.15 Delineating the void by the common tangent line of ellipses (after Ge, 2006).]
6.5.2 Computer Program for Ellipse Plotting

Only two pieces of information are needed for ellipse plotting: the coordinates of the source and the receiver, the travel distance of reflection which is the product of the signal arrival time, and the associated velocity of the signal.

- **Coordinates of source and receiver**

  The locations of source and receiver are the foci of the ellipse. For the elliptical mapping method, there is no specific requirement on how they should be located. However, the coordinates of the source and the receiver should be accurate. Caution has to be taken when preparing the coordinate data that the coordinates should be the actual positions of sensors and explosives, not the borehole collars. Once the coordinates are known, the distance between them is determined and parameter $c$ used in Eq. 6.2 can be calculated by the equation: $2c = \text{distance between the source and the receiver}$.

- **Reflection travel distance**

  The travel distance of reflection is the product of the signal arrival time and the associated velocity of the signal. The signal travel time is the signal arrival time minus the time of the blast detonation (trigger time). Associated with the signal arrival time, another important property of a signal is the signal type or signal phase because each signal type or phase has its own velocity. Once the signal type is determined, the corresponding signal velocity can be determined by a transmission test.

- **Computer Program**

  A MatLAB program is compiled for the ellipse plotting. For programming, Eq (6.1) is rewritten as
\[
\begin{align*}
  x &= a \sin(t) \\
  y &= b \cos(t) \\
  (t &= 0 \sim 2\pi)
\end{align*}
\]

Then an ellipse can be plotted at the origin with the major axis \( a \) and minor axis \( b \). After rotating and parallel displacement, ellipses can be plotted at any location with any angle.

In order to draw ellipses, two input files are needed: the coordinates file and the travel distance file. The coordinates file contains the survey data of the blasting source and the sensor location. The travel distance file contains the corresponding travel distance for each sensor-source coordinate data. The MatLAB program code for ellipse plotting is given in Appendix F.

**6.5.3 Mine Void Delineating**

Because of inevitable errors in the input data, the common tangent line has to be defined statistically since there is no common tangent line for all ellipses. For the ISS-based void detection, a common tangent has to satisfy the following conditions: 1) a straight line defined within a specified section, 2) which has the least distance errors from the ellipses, and 3) the directions of the reflectors (the tangent lines of the individual ellipses) are in the same direction of the common tangent line. It is clear that the common tangent line is the best fit of all involved ellipses.

**6.6 Case Studies**

In this section, two events, Event 53 and Event 89, are utilized to demonstrate the void mapping process.
6.6.1 Event 53

Event 53 is a reflection survey. The experimental layout, including the borehole location (R16) and the associated ray paths, are illustrated in Figure 6.16.

![Harmony Mine Site II Map and Experiment Setup](image)

**Figure 6.16** Test layout of Event 53 and the potential reflection ray path.

The original waveform of the event is given in Figure 6.17 part (a). The trigger time for the event is at 0.05 second shown by Channel 1, which is the triggering channel. There are two major wave groups in the transmitted data as marked: refracted S-waves emerged at around 80 ms and transmitted Love waves at around 100 ms. The trend of the
Love waves was enhanced significantly after applying a bandpass filter of 200–600 Hz as shown in part (b).

Figure 6. 17 Original waveform and bandpass filtered waveform of Event 53. A trend of transmission Love waves with sharp arrival time was present after filtering.
In Figure 6.17, refracted P- and S- waves and transmitted Love waves dominate the waveform. To enhance the appearance of reflection signals, those transmitted waves were ‘muted’ by applying velocity 1067 m/s (3500 ft/s) windowing. The ‘muted’ signals were then processed by a bandpass filter and the wavelet transform. The results are shown in Figure 6.18.

Figure 6.18 Bandpass filtering and wavelet transform for reflected signals of Event 53.
The arrival time of the reflection signals and the reflection distance are listed in Table 6.3.

Figure 6.19 shows the result of void detection, which has a very small mapping error.

<table>
<thead>
<tr>
<th>CH. No.</th>
<th>Sensor No.</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>14</th>
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<tr>
<td>Time (ms)</td>
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<td>148.9</td>
<td>149.7</td>
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<td>150.4</td>
<td>153.1</td>
<td>157.5</td>
<td>158.6</td>
<td>160.3</td>
<td>161.1</td>
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<tr>
<td>Distance (ft)</td>
<td>S2</td>
<td>317</td>
<td>320</td>
<td>328</td>
<td>322</td>
<td>330</td>
<td>344</td>
<td>348</td>
<td>353</td>
<td>356</td>
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</tbody>
</table>

Figure 6.19 Elliptical void mapping by Event 53 (velocity=975 m/s (3200 ft/s)).
6.6.2 Event 89

The source of Event 89 is R8 with 125 grams of explosive. The layout of the test and the possible reflection ray path are shown in Figure 6.20.

![Harmony Mine Site II Map and Experiment Setup](image)

**Figure 6.20 Test layout of Event 89 and the potential reflection ray path.**

Having favorable conditions for both transmission and reflection, Event 89 has been discussed thoroughly before. Readers can refer to Figures 4.1, 4.9, 4.10, 5.8, 5.12, 5.13, 5.17, 5.18, 5.20, 5.21, 6.2, 6.5, 6.7~6.13 for more details about this event.
The reflected signals were relatively strong after the bandpass filter and wavelet transform (Figure 6.21).
The arrival time of the reflection signals and the reflection distance are listed in Table 6.4. Figure 6.22 shows the result of void detection, which has a very small mapping error.

Table 6.4 Arrival time reading of reflection signal and travel distance by velocity of 975 m/s (3200 ft/s).

<table>
<thead>
<tr>
<th>CH. No.</th>
<th>Sensor No.</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>13</th>
<th>14</th>
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<tr>
<td></td>
<td>S6</td>
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<td>S9</td>
<td>S10</td>
<td>S12</td>
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</tr>
<tr>
<td>Time (ms)</td>
<td></td>
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<td>152.3</td>
<td>153</td>
<td>153.2</td>
<td>154.4</td>
<td>154.6</td>
<td>155.8</td>
<td>156.6</td>
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<tr>
<td>Distance (ft)</td>
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<td>330.2</td>
<td>334.0</td>
<td>334.7</td>
<td>338.5</td>
<td>341.1</td>
</tr>
</tbody>
</table>

Figure 6.22 Elliptical void mapping by Event 89 (velocity=975 m/s (3200 ft/s)).
6.7 Void Mapping Results

The following presents the void mapping results by the elliptical mapping method, with reflection data on Event 53, 72, 85, and 89. Please note that the ‘void’ actually is the mine entry whose location can be determined by a mine survey. Therefore, the void mapping results can be checked by the actual position of the reflectors.

At Harmony Mine Site II, the void location and the result of the elliptical method are shown in Figure 6.23. The pillar boundary in this case is well fitted by two red lines, the common tangential lines of the groups of ellipses.

Figure 6.23 Elliptical void mapping at Harmony Mine Site II.
It is noted that the void boundary appears to be defined by two reflectors. Corresponding to this feature, the ellipses can be divided into two groups. One group includes those which were associated with sources R11, R13, and R16 (Figure 6.24a). The signals originated with these sources could be reflected from either section, depending on the sensor locations. The ellipses belonging to the second group were associated with three other sources: R7, R8, and R9 (Figure 6.24b). The signals corresponding to these sources were all reflected from the closer reflector.

Figure 6.24 Two sets of ellipses by different reflectors at Harmony Mine Site II.
Figure 6.24 Two sets of ellipses by different reflectors at Harmony Mine Site II.

Figure 6.24 shows that the void boundaries at AB and CD were delineated fairly accurately. The mapping error at the site was in the order of ±4.6 m (15 ft).

6.8 Summary and Discussion

The elliptical void mapping method provides a simple and convenient means for void detection. It can utilize all signals reflected from a similar location to delineate the void boundary in the area, regardless of the locations of sources and receivers, the type of signals, and the survey sequence. As the method represents the reflection data directly, it
avoids many mathematical manipulations that would be required, if other methods were used. However, it should be emphasized that, although the final result is shown by the mapping method, this is only one of the components necessary to obtain a reliable result. The necessary components for the reliable results are based on careful experimental design and accurate signal analysis, arrival time picking and velocity determination. Therefore, the results of satisfactory elliptical void mapping validated the feasibility of the overall techniques applied in this research.
Chapter 7
CONCLUSIONS AND RECOMMENDATIONS
FOR FUTURE RESEARCH

7.1 General Summary and Conclusions

In order to improve underground coal mine safety, an in-seam seismic (ISS) based void
detection technique was developed and successfully tested at the Harmony Mine (Ge, 2006). The author of this thesis actively participated in the development work of this
technique from the beginning, including laboratory and field tests, routine data analysis,
and theoretical development. The first purpose of this thesis is thus to provide an
overview of the technique. The second and main content of this thesis is to introduce the
authors original work on the wavelet transform for ISS data analysis. This is the focus of
this thesis and the main contribution made by the author.

7.1.1 The ISS-based Void Detection Technique

The research discussed in this thesis is part of a large effort aimed at developing a reliable
ISS-based mine void detection technique (Ge, 2006). The key components of the
technique are experimental design, data analysis, and void mapping. Knowledge of these
components is not only important for understanding the technique, but is also essential
for understanding the role of the data analysis techniques developed by the author.

Experimental design is one of the most critical steps for the ISS-based void detection
technique. The purpose of experimental design is to create the best test situation for
acquiring high quality signals and to construct a stable mathematical system for data analysis. Four components of experimental design, including testing layout, data acquisition system and sensors, sensor installation, and seismic sources, have been discussed.

The development of a high quality retrievable sensor installation technique is especially important for the ISS-based void detection technique. The technique developed made it possible to acquire high quality, broadband signals.

Signal analysis is another important part of the ISS-based void detection technique. The ISS data for void detection featured multiple arrivals, dispersive Love waves, and weak reflection signals. In order to deal with these problems, a comprehensive data analysis procedure was needed. In this research, several data analysis approaches and methods were used, including physical inspection, polarization analysis, the Fourier transform and wavelet analysis. The suitability of the signal analysis procedure was examined using real data obtained from the Harmony Mine. The signal analysis results obtained demonstrated that these signal analysis methods were reliable and efficient.

Void mapping was carried out using the elliptical void mapping method. The method provides a simple and convenient means for void detection. It can utilize all signals reflected from a similar location to delineate the void boundary in the area, regardless of the locations of sources and receivers, the type of signals, and the survey sequence. As the method represents the reflection data directly, it avoids many mathematical manipulations which would be necessary if the other methods are used. This characteristic makes the method much more stable than any other method.
7.1.2 Wavelet Based Signal Analysis Methods

The main contribution of the author for the ISS-based void detection technique was the development of wavelet based signal analysis methods. Wavelet analysis, a mathematical tool for studying non-stationary frequency characteristics, was found especially efficient and powerful for ISS signal analysis. Three critical problems of the ISS technique, including signal identification, dispersion analysis, reflection signal detection, were studied with wavelet analysis.

Signal identification of channel waves is an essential task for signal analysis. Arrival time determination for these signals is challenging as they are often superimposed by body waves. However, a unique function of wavelet analysis is that wavelet transform can study a signal in the time and frequency domains simultaneously, which provides an insight into the signal. The wavelet transform thus provides much more information than the Fourier transform by simultaneously tracking the time and frequency. The wavelet transform is also more accurate than other methods for arrival time picking for transient signals with a very short time period and high frequencies. A 3D display of the wavelet transform illustrated the relations between P-waves, S-waves, and Love waves, which is very helpful for recognizing the pattern of recorded seismic signals. It also provides a convenient tool to identify the arrival time of seismic signals by examining their time-related frequency characteristics, and makes it an ideal method to determine different types of seismic signals.

The estimation of dispersion characteristics of in-seam seismic waves is the most important aspect of ISS signal analysis. The extraction of dispersion curves from
transmission surveys can be conducted in different ways. There are major drawbacks with manually reading the peak and trough arrival times. The multiple filter technique is a commonly used method, but this procedure is time-consuming and the manual selection of the frequency and arrival time is very difficult. An advanced method introduced and developed in this current research associated with ISS signal analysis is the wavelet transform based dispersion analysis (WTDA), which has proven to be a very efficient and fast method for dispersion analysis. Since the unique function of the wavelet transform is to convert a signal in the time domain into the time-frequency domain at the same time, the WTDA does not need to determine the arrival time and the frequency of the bandpass filter by hand. This makes the computational procedure of dispersion analysis fast and efficient. Dispersion curves obtained by the WTDA procedure for the Harmony Mine signals show that the velocity-frequency relationship of the body waves may have different characteristics for different signals, but the velocity-frequency relationship of the Love waves is very consistent. The dispersion characteristics of Love waves were carefully studied at the Harmony Mine with the WTDA. In general, the Love waves had a frequency range of 300 – 900 Hz with a velocity range of 1372 – 914 m/s (4500 – 3000 ft/s). The typical frequency range for the Airy-phase of the Love wave was 400 – 600 Hz with a stable velocity of 975 m/s (3200 ft/s). Dispersion analysis using the wavelet transform not only proves the presence of channel waves, but also determines a reliable channel wave velocity which is critical for ISS-based mine void detection.

In-seam seismic signals, especially reflection channel waves, are often buried in noise signals. Wavelet decomposition and reconstruction has been proven to be a very useful tool to separate Love waves from noises. Wavelet analysis also provides an ideal means
for detecting newly emerged signals and reflection signals whose signal-to-noise-ratio is relatively small. With the help of wavelet decomposition, many reflected signals, which are difficult to see in the original waveforms, can be enhanced and identified.

7.2 Recommendations for Future Research

In order to improve the practicability and reliability of the ISS-based void detection technique, several additional issues need to be studied, namely: 1) a further study to identify differences between a water or air-filled mine void, 2) further research to develop wireless sensors and a more sophisticated data acquisition system, and 3) further field experiments to validate the technique with blind tests.

7.2.1. Water or Air-Filled Mine Voids

An important question associated with void detection is to determine if the void filled with water or air. Water-filled mine voids in general pose more of a threat to mine safety than do air-filled ones.

In order to find a reliable answer to this question, field tests need to be carried out under both conditions. So far, the ISS tests were carried out successfully at an underground mine section filled with air. Further research in this field on water-filled voids is therefore highly recommended. A potential challenge will be signal analysis to compare the characteristics of reflection signals under both conditions.

7.2.2. Wireless Sensors and Data Acquisition System
The data acquisition system currently used for this project has many advantages, such as broadband data acquisition ability and permissible license issue by MSHA. However, there are two problems with the current system. One is the lack of mobility and the other is the time necessary to set up the system. With the recent fast development of computer technology, further research to develop more sophisticated data acquisition systems is recommended.

The use of ‘wireless’ techniques could make the ISS field tests much easier and faster. The ‘Wi-Fi’ revolution has provided equipment designers with highly integrated, low-cost components. A wireless seismograph now can be designed and sold for less than the price of a traditional multi-channel instrument. A multi-channel wireless seismograph with wireless triggering could be less expensive, more reliable and flexible, and much lighter than a wired system.

7.2.3. Void Mapping with Blind Tests

The elliptical void mapping results at Harmony Mine show an excellent fit between the envelope of the elliptics and the known void boundary. However, blind tests without prior information on the void boundary are necessary for practical proof of the technique. For a blind test and subsequent practical application of the ISS technique in the mining industry, researchers have to deal with the complexity of the reflection signals without the knowledge of the anticipated reflection time. Other techniques, such as pattern recognition, statistics study, should also be topics of future studies.
REFERENCES


Millahn, K. O., (1980), “Two component in-seam seismic”, 50th international SEG-meeting, Houston, USA.


Appendix A

Graphic Solution for Dispersion Curve

% 1. Dispersion Demo
% Group and phase velocity Demonstration

% w is angle frequency 2*pi/T and T=0.1
w=10*2*pi;
dleta_w=5;
w1=w+dleta_w; w2=w-dleta_w;
% k is wavenumber 2*pi/lambda=w/v, suppose phase velocity c=5
C=5;
k=w/C; % k is 4*pi=12.56
delta_k=1.5;
k1=k+delta_k;k2=k-delta_k;

%%%%%%%%%%%%%%%%%%%%%%%%%
t=0;
x=0:0.01:6;
u1=sin(w1*t-k1*x);
u2=sin(w2*t-k2*x);

subplot(5,1,1), plot(x,u1);title('a:  u1=sin(w1*t-k1*x)')
subplot(5,1,2), plot(x,u2);title('b:  u2=sin(w2*t-k2*x)')

u=sin(w1*t-k1*x)+sin(w2*t-k2*x);
% envelope
ug=2*sin(5*t+1.5*(x-3.1));
subplot(5,1,3), plot(x,u); title('c:   u(x,t), t=0');hold on;
plot(x,ug,'r'); hold on;
plot(x,-1*ug,'r');

% t=0.1;
u=sin(w1*t-k1*x)+sin(w2*t-k2*x);
% groupe velocity equals dleta_w/dleta_k=5/1.5
ug=2*sin(5*t+1.5*(x-3.1-0.1*2*5/1.5));
subplot(5,1,4), plot(x,u);title('d:   u(x,t), t=0.1');hold on;
plot(x,ug,'r'); hold on;
plot(x,-1*ug,'r');

% t=0.2;
u=sin(w1*t-k1*x)+sin(w2*t-k2*x);
% envelope
ug=2*sin(5*t+1.5*(x-3.1-0.2*2*5/1.5));
subplot(5,1,5), plot(x,u);title('e:   u(x,t), t=0.2');hold on;
plot(x,ug,'r'); hold on;
plot(x,-1*ug,'r');

% 2. Graphic Solution for dispersion curve calculation
% For PhD thesis chapter 2 background theory
%%% parameters
% coal seam at harmony mine is around 2h=4 ft
h=2;
% density of coal
d_c=94;
% density of rock
d_r=145;
% shear wave velocity of coal (S wave 3600 ft/s is from literature for hard coal)
s_c=3600;
% shear wave velocity of rock
s_r=8000;

% frequency (Hz)
f=1000;
w=2*pi*f;
% apparent velocity
c_x=s_c:10:s_r;
%%% length
s=length(c_x);

%%% plots
% figure;
for i=1:s
t(i)=h*sqrt(1/(s_c)^2-1/(c_x(i))^2);
end
% left side of equation
L=tan(w*t);
plot(c_x,L); title('Frequency f=5000 Hz'); xlabel('Velocity c_x'); grid on;
plot(t,L); title('Frequency f=5000 Hz'); hold on;

%% right side of the equation
for i=1:s
t(i)=h*sqrt(1/(s_c)^2-1/(c_x(i))^2);
R(i)=d_r/(d_c/t(i))*sqrt(1/(c_x(i))^2-1/(s_r)^2);
end
figure; % figure with t as x-axes
plot(t,L); hold on; plot(t,R,'r'); axis([0,t(s),-10,10]); xlabel('t=h*sqrt(1/(s_c)^2-1/(c_x)^2)'); grid on;

figure;
%%% another figure with frequency as x-axes
plot(c_x,L); hold on; %title('Frequency f=1000 Hz');
plot(c_x,R,'r'); axis([s_c,s_r,-10,10]); xlabel('velocity (ft/s)'); grid on;
Appendix B

Sensitivity Analysis

1. Introduction

Reflection survey is the field test of ISS using reflected signals detecting mine voids. Travel distance calculation and analysis is critical for the reflection survey. There are four main purposes for travel distance analysis. First, approximate reflection distance is necessary for experiment design, as the timing window of the data acquisition system is limited. For example, if the reflection time is anticipated to be more than 0.4 second, a 0.8 window has to be considered. Second, Anticipated arrival time reading, which is very important for the search and identification of reflected signals, is based on the calculation of signal velocity and reflection distance. Third, reflection distance analysis is the main criteria for the trend of multi-channel reflection. The inclination of the stacking is mostly dependent on the reflection distance differences. Four, reflection distance is necessary for velocity calculation of reflected waves. This chapter will discuss the calculation of reflection distance and sensitivity analysis.

2. Derivation of travel distance for reflection survey

As shown in Figure B-1, \(AB\) is survey line; \(A'B'\) is reflection line (reflector). \(A\) is source and \(B\) is receiver. Suppose the distance between \(A\) and \(B\) is \(f\), the distance from \(A\) to reflection line \(A'B'\) is \(h\), and the angle between \(OB\) and \(OB'\) is \(\alpha\). \(A''\) and \(A\) are symmetric related to the line of \(A'B'\) (\(A''\) is named as ‘Virtual source’ and \(A\) is ‘real source’ (Mason, 1980).

\[\alpha\]

Figure B-1 Diagram for the derivation of reflection distance

\(ACB\) is the ‘ray path’ of the reflection, \(C\) is reflection point and \(\beta\) is incidence angle.
As known:
\[ AA' = h; \ AB = f; \]
\[ \angle A'O'A = \alpha; \ \angle ACD = \angle DCB = \beta; \ DC \perp A'B'; \]
\[ AA'' \parallel DC \parallel BB'; \]
\[ A''A' = A'A. \]

For derivation, set: \( OA = m; \)

From the definition of triangle functions:
\[
AC = A'C / \sin(\beta); \\
CB = CB'/\sin(\beta); \\
A'B' = AB \cdot \cos(\alpha)
\]

Combining Eq. (1) and Eq. (2),
\[
AC + CB = (A'C + CB') / \sin(\beta) \\
= A'B'/\sin(\beta)
\]
Substituting \( A'B' \) from Eq. (4) into Eq. (3), the travel distance for reflection survey,
\[
AC + CB = AB \cdot \cos(\alpha) / \sin(\beta) \\
= f \cdot \cos(\alpha) / \sin(\beta)
\]

The Next step is to calculate \( \sin \beta \).

As \( \triangle AA'A''C \) and \( \triangle B'B'C \) are ‘similar triangles’, so,
\[
\frac{A'C}{CB'} = \frac{A''A'}{B'B'}
\]
as known,
\[
A''A = A'A,
\]
so
\[
\frac{A'C}{CB'} = \frac{A'A}{B'B'},
\]
and as \( A'A \parallel BB' \),
\[
\frac{A'A}{B'B} = \frac{OA}{OB} = \frac{m}{m + f}.
\]
Combining Eq. (8) and Eq. (9),
\[
\frac{A'C}{CB'} = \frac{m}{m + f};
\]
Then
\[
\frac{A'C}{A'B'} = \frac{A'C}{(A'C + CB')} = \frac{m}{2m + f}
\]  

(11)

And as

\[
A'B' = AB \cdot \cos(\alpha) = f \cdot \cos(\alpha)
\]  

(12)

Combining Eq. (11) and Eq. (12),

\[
A'C = f \cdot \cos(\alpha) \frac{m}{2m + f} ;
\]  

(13)

Also, it is known:

\[
AA' = OA' \cdot \sin(\alpha) = m \cdot \sin(\alpha),
\]  

(14)

Therefore, with equation (13) and (14):

\[
\tan(\beta) = \frac{A'C}{AA'} = \frac{f \cdot \cos(\alpha) \frac{m}{2m + f}}{m \cdot \sin(\alpha)}
\]  

(15)

\[
\sin \beta = \frac{f \cdot \ctg(\alpha)}{\sqrt{(2m + f)^2} + [f \cdot \ctg(\alpha)]^2}
\]  

(16)

Substituting \(\sin \beta\) from Eq. (16) into Eq. (15), the travel distance defined as \(2L\):

\[
2L = AC + CB = f \cdot \cos(\alpha) / \sin(\beta)
\]  

\[
= \frac{f \cdot \cos(\alpha)}{f \cdot \ctg(\alpha)}
\]  

\[
= \frac{1}{\sqrt{(2m + f)^2} + [f \cdot \ctg(\alpha)]^2}
\]  

(17)

Substituting \(m = \frac{h}{\sin(\alpha)}\) into Eq. 17,
Therefore, the travel distance can be calculated as:

\[ 2L = \sqrt{\left(2 - \frac{h}{\sin(\alpha)} + f\right)^2 + \left[f \cdot \cot(\alpha)\right]^2 \cdot \sin(\alpha)} \]

\[ = \sqrt{\left[(2h + f \sin(\alpha))^2 + f^2 \cos^2(\alpha)\right]} \]

\[ = \sqrt{4h^2 + f^2 + 4hf \sin(\alpha)} \]  

(18)

Therefore, the travel distance can be calculated as:

\[ 2L = \sqrt{4h^2 + f^2 + 4hf \sin(\alpha)} \]  

(19)

where \(2L\) is the total reflection distance, \(h\) is the distance from source to reflection line, \(f\) is the distance between source and receiver, and \(\alpha\) is the angle between survey line and reflection line.

End of Derivation.

3. Validation

To check the validation of the derivation, there is another way to get this equation. According to ‘cosine principle of triangle’, for any triangle,

\[ a^2 = b^2 + c^2 - 2bc \cdot \cos(A) \]  

(20)

From Figure.1, \(A''A = 2h\), \(AB = f\);

As

\[ \angle A^\prime AC = \angle AOC = \alpha, \quad \angle A^\prime OA = 90^\circ, \]  

(21)

And

\[ \angle A''AB = \angle AOC + \angle A^\prime OA, \]  

(22)

Combining Eq.(21) and Eq. (22)

\[ \angle A''AB = 90^\circ + \alpha. \]  

(23)

Submitting the above parameters into Eq. (20),
\[(A''B)^2 = (A''A)^2 + (AB)^2 - 2 \cdot (A''A) \cdot (AB) \cdot \cos(\angle A''AB)\]
\[= (2h)^2 + f^2 - 2 \cdot 2h \cdot f \cdot \cos(90^\circ + \alpha)\]
\[= 4h^2 + f^2 + 4hf \sin(\alpha)\]  \hspace{1cm} (24)

And as \(A''B = AC + CB = 2L\),

Therefore, the travel distance can be calculated as:
\[2L = \sqrt{4h^2 + f^2 + 4hf \sin \alpha}\]  \hspace{1cm} (25)

End of prove.

4. Sensitivity Analysis

Suppose there is a small change of the reflection distance \(2\Delta L\) due to velocity or timing error, accordingly there will be a small change of the calculated distance \(\Delta h\) from the source to the reflection line (see Figure B-2), where \(BN = BA', MN = \Delta L\).

Assume M is the new ‘Virtual source’ of A, related to the new reflector, then \(MA'' = 2\Delta h\). If the travel distance change \(2\Delta L\) is small, then \(\angle MBA''\) is very small, and \(\Delta MNA''\) can be regarded as rectangle triangle, where \(\angle MNA'' = 90^\circ\).

![Figure B-2. Diagram for the derivation of reflection distance sensitivity](image)

Therefore,
\[2\Delta h = \frac{2\Delta L}{\cos(\gamma)};\]  \hspace{1cm} (26)
Recall the principle of triangle of Eq. (20),

$$\cos(\gamma) = \frac{(2h)^2 + (2L)^2 - f^2}{2(2h \cdot 2L)}; \quad (27)$$

Substituting $\cos(\gamma)$ from Eq. (27) into Eq. (26),

$$\Delta h = \frac{2h \cdot 2L}{(2h)^2 + (2L)^2 - f^2} \cdot 2\Delta L \quad (28)$$

From equation 19,

$$2L = \sqrt{4h^2 + f^2 + 4hf \sin \alpha} \quad (29)$$

Substituting $L$ from Eq. (29) into Eq. (28), the calculated reflector location difference will be

$$\Delta h = \frac{2h \cdot \sqrt{4h^2 + f^2 + 4hf \sin(\alpha)}}{(2h)^2 + 4h^2 + f^2 + 4hf \sin(\alpha) - f^2} \cdot 2\Delta L$$

$$= \frac{h \cdot \sqrt{4h^2 + f^2 + 4hf \sin(\alpha)}}{4h^2 + 2hf \sin(\alpha)} \cdot 2\Delta L$$

$$= \frac{\sqrt{4h^2 + f^2 + 4hf \sin(\alpha)}}{2h + f \sin(\alpha)} \cdot \Delta L \quad (30)$$

The result shows that if there is travel distance change ($2\Delta L$) due to velocity or timing error, the correlated change of distance ($\Delta h$) from the source to the reflection line will be

$$\Delta h = \frac{\sqrt{4h^2 + f^2 + 4hf \sin \alpha}}{2h + f \sin \alpha} \Delta L \quad (31)$$

Where, where $\Delta h$ is the error of the reflector, $\Delta L$ is half of the error of reflection distance, $h$ is the distance from source to reflection line, $f$ is the distance between source and receiver, and $\alpha$ is the angle between survey line and reflection line.

5. An example

If $\alpha = 0^\circ$, the travel distance ($2L$) will be:

$$2L = \sqrt{4h^2 + f^2} = \sqrt{(2h)^2 + f^2}.$$ This can be confirmed by Figure 5.
Figure B-3 Reflection ray path if survey line and reflection line are parallel.

\[
\frac{dL}{dh} = \frac{1}{2} \frac{4h}{\sqrt{4h^2 + f^2}} = \frac{2h}{\sqrt{4h^2 + f^2}} \quad (32)
\]

\[
dh = \frac{\sqrt{4h^2 + f^2}}{2h} \cdot dL = \frac{2L}{2h} \cdot dL = \frac{L}{h} \cdot dL \quad (33)
\]

Or

\[
\Delta h = \frac{L}{h} \cdot \Delta L \quad (34)
\]

Since, \(\sin \theta = \frac{h}{L}\), an alternative form for Eq. 34 is

\[
\Delta h = \frac{\Delta L}{\sin \theta} \quad (35)
\]

Equation 35 shows that the error for the void distance is governed by the relative dimension of the void distance and the distance between the sensor and the source. If \(\theta\) is small, a minor initial error, such as arrival time reading or velocity error, could cause a large mapping error.
Appendix C

Hodogram Analysis

%% Hodogram analysis with animation
%%
load H2E89.m;
%%%% load signals
wave=H2E89(:,[4]);
figure;
%%bandpass filtering
[B2,A2]=cheby1(4,3,[100/10000/0.5,1000/10000/0.5]);
% c%h9 and ch10 is one pair
%suppose ch9 is x axis, and ch10 is y axis
channel9=wave(8192*8: 8192*9);
ch9=filter(B2,A2,channel9);
% channel10=wave(8192*9: 8192*10);
ch10=filter(B2,A2,channel10);

% sample rate 20k
t=0:1/20000:8192/20000;
%time window 50 ms to 120 ms
tmin=1000; tmax=2400;
%plot
subplot(2,7,1:7),plot(t(tmin:tmax),ch9(tmin:tmax)+2); hold on;
ylabel('ch10(S9)           ch9(S8)');
subplot(2,7,1:7),plot(t(tmin:tmax),ch10(tmin:tmax)+1); grid on;
title('100~1000 hz ch9 and ch10');
axis([0.05 0.12 0.5 2.5]);
%%%%
% w=tmax-tmin;
% for i=1:w/10
%   hx(i)=ch9(tmin+i*10);
%   hy(i)=ch10(tmin+i*10);
%end
subplot(2,7,8),plot(ch9(tmin+1:tmin+200),ch10(tmin+1:tmin+200),'r');title('hodogram at window 50~60 ms'); axis([-0.3 0.3 -0.3 0.3]);
subplot(2,7,9),plot(ch9(tmin+201:tmin+400),ch10(tmin+201:tmin+400), 'r');title('60~70 ms'); axis([-0.3 0.3 -0.3 0.3]);
subplot(2,7,10),plot(ch9(tmin+401:tmin+600),ch10(tmin+401:tmin+600), 'r');title('70~80 ms'); axis([-0.3 0.3 -0.3 0.3]);
subplot(2,7,11),plot(ch9(tmin+601:tmin+800),ch10(tmin+601:tmin+800), 'r');title('80~90 ms'); axis([-0.3 0.3 -0.3 0.3]);
subplot(2,7,12),plot(ch9(tmin+801:tmin+1000),ch10(tmin+801:tmin+1000), 'r');title(' 90~100 ms'); axis([-0.3 0.3 -0.3 0.3]);
subplot(2,7,13), plot(ch9(tmin+1001:tmin+1200),ch10(tmin+1001:tmin+1200) , 'r'); title(' 100~110 ms'); axis([-0.3 0.3 -0.3 0.3]);

subplot(2,7,14), plot(ch9(tmin+1201:tmin+1400),ch10(tmin+1201:tmin+1400) , 'r'); title(' 110~120 ms'); axis([-0.3 0.3 -0.3 0.3]);

%%%% hodogram movie

load channel9.mat;
load channel10.mat;

%%time window (ms)
tmin=60; tmax=70;
t=tmax-tmin;

%movie
mv=zeros(8192,1);

for i=1:20*t
    axis([-0.4,0.4,-0.4,0.4]); grid on;
    %axis tight
    plot(channel9(i+tmin*20+1),channel10(i+tmax*20+1),'r*');
    hold on;
    plot(channel9(i+tmin*20:i+tmin*20+1),channel10(i+tmin*20:i+tmin*20+1), 'r');
    mv(i)=getframe;
end
movie(mv,1,200);
movie2avi(mv,'hodogram 60~70 ms of E89 ch9 and ch10');
Appendix D

Wavelet Decomposition

% Load the original 1-D signal, decompose, and reconstruct details in
% original time and plot.
% Load the signal.
clear; clc;
load H2E89.m;

wave = H2E89(:, [4]);
figure;
j = 1;
ch = wave(8192 * j + 1: 8192 * (j + 1));
s = ch(1:3001);
% Decompose the signal s at level 6 using the wavelet db10.
w = 'db10';
[c, l] = wavedec(s, 6, w);

% Reconstruct the details using the decomposition structure.
for i = 1:6
    D(i, :) = wrcoef('d', c, l, w, i);
end

% Avoid edge effects by suppressing edge values and plot.
tt = 1 + 100:length(s) - 100;
t = tt / 20000;
subplot(7, 1, 1); plot(t, s(tt), 'r'); ylabel('s');
title('H2E89 Ch2 Signal and Details');
for i = 1:6, subplot(7, 1, i + 1); plot(t, D(6 - i + 1, tt), 'k'); ylabel('d');
end
Appendix E

Wavelet Based Dispersion Analysis

% Wavelet Transform based Dispersion Analysis for In-Seam Seismic
% Signal Processing
% by Hongliang Wang on July 7, 2007

clear,clc;
figure;

load H2E43Ch3.txt;
time=(1000:3000)/20; %/:1/20000:3000/20000;
    subplot (3,1,1), plot(time', H2E43Ch3(1000:3000));
    title('Wavelet Transform H2E43Ch3');xlabel('original signal');
ylabel('amplitude');

%load wavelet coef which was calculated with Gabor wavelets.
load h2e43ch3_wavelet_coef.txt;
%sample rate 10000
    t=h2e43ch3_wavelet_coef(:,1)/1000; t(1)=[];
    f=h2e43ch3_wavelet_coef(1,:)*1000; f(1)=[];
    h2e43ch3_wavelet_coef(1,:)=[];
    h2e43ch3_wavelet_coef(:,1)=[];
    wvltcoef=h2e43ch3_wavelet_coef;
    subplot (3,1,2), contour(t',f,wvltcoef');
% dispersion analysis:
%transmission distance: 219.5 ft from blasting source T1 to receiver S1
    d=230.5*32/28;
%velocity v=d/t trigger time 50 ms
    v=d./(t-49.99)*1000;
    subplot (3,1,3), contour(f,v,wvltcoef');axis ([0,1000,2000,10000]);
ylabel('velocity (ft/s)'); xlabel('frequency (Hz)');

% zoom in
figure;
contour(f,v,wvltcoef');axis ([0,1000,2000,10000]);
ylabel('velocity (ft/s)'); xlabel('frequency (Hz)');
title('Wavelet based Dispersion Analysis H2E43Ch3')
% written by H.Wang, Penn State University, courtesy of ellipse.m
% original written by D.G. Long, Brigham Young University, and
% CIRCLES.m original written by Peter Blattner, Institute of
% Microtechnology, University of Neuchatel, Switzerland

function [a,b,c] =ellipse3(F1,F2,d)
%This is a function to demonstrate how to plot ellipse.
%F1(x1,y1), F2(x2,y2) and travel distance d are input data.

x1=F1(1); y1=F1(2);
x2=F2(1); y2=F2(2);
x0=(x1+x2)/2; y0=(y1+y2)/2;

%%
% plot focus
f1=char(F1); f2=char(F2);
%focus1='f1',focus2='f2';
plot(x1,y1,'m*');text(x1,y1,'f1');
hold on;
plot( x2,y2,'^');text(x2,y2,'f2');

%%
c=sqrt((x1-x2)^2+(y1-y2)^2)/2;
if d<=2*c
    error('Error! d is small than 2c! The travel distance must be bigger than the distance from F1 to F2 !');
    return;
end
a=d/2;
b=sqrt(a^2-c^2);
if x1==x2
    q0=pi/2;
else
    q0=atan((y2-y1)/(x2-x1));
end
ellipse(a,b,q0,x0,y0,'b',300);
grid on;

%This is a function to plot ellipse.

function h=ellipse(ra,rb,ang,x0,y0,C,Nb)
% Check the number of input arguments

if nargin<1,
    ra=[];
end;
if nargin<2,
    rb=[];
end;
if nargin<3,
ang=[];
end;

%i nargout==1,
% error('Not enough arguments');
%end;

if nargin<5,
x0=[];
y0=[];
end;

if nargin<6,
C=[];
end
if nargin<7,
Nb=[];
end

% set up the default values
if isempty(ra),ra=1;end;
if isempty(rb),rb=1;end;
if isempty(ang),ang=0;end;
if isempty(x0),x0=0;end;
if isempty(y0),y0=0;end;
if isempty(Nb),Nb=300;end;
if isempty(C),C=get(gca,'colororder');end;

% work on the variable sizes
x0=x0(:);
y0=y0(:);
ra=ra(:);
rb=rb(:);
ang=ang(:);
Nb=Nb(:);
if isstr(C),C=C(:);end;

if length(ra)==length(rb),
    error('length(ra)==length(rb)');
end;
if length(x0)==length(y0),
    error('length(x0)==length(y0)');
end;

% how many inscribed ellipses are plotted
if length(ra)==length(x0)
    maxk=length(ra)*length(x0);
else
    maxk=length(ra);
end;
% drawing loop

for k=1:maxk

    if length(x0)==1
        xpos=x0;
        ypos=y0;
        radm=ra(k);
        radn=rb(k);
        if length(ang)==1
            an=ang;
        else
            an=ang(k);
        end;
    elseif length(ra)==1
        xpos=x0(k);
        ypos=y0(k);
        radm=ra;
        radn=rb;
        an=ang;
    elseif length(x0)==length(ra)
        xpos=x0(k);
        ypos=y0(k);
        radm=ra(k);
        radn=rb(k);
        an=ang(k);
    else
        rada=ra(fix((k-1)/size(x0,1))+1);
        radb=rb(fix((k-1)/size(x0,1))+1);
        an=ang(fix((k-1)/size(x0,1))+1);
        xpos=x0(rem(k-1,size(x0,1))+1);
        ypos=y0(rem(k-1,size(y0,1))+1);
    end;

    co=cos(an);
    si=sin(an);
    the=linspace(0,2*pi,Nb(rem(k-1,size(Nb,1))+1,:)+1);
    x=radm*cos(the)*co-si*radn*sin(the)+xpos;
    y=radm*cos(the)*si+co*radn*sin(the)+ypos;
    h(k)=line(radm*cos(the)*co-si*radn*sin(the)+xpos,radm*cos(the)*si+co*radn*sin(the)+ypos);
    set(h(k),'color',C(rem(k-1,size(C,1))+1,:));

end;

%%%%%%%%%%%%%%%%
VITA

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