MOBILE ACOUSTIC SENSING OF SURFACE WAVES FOR ROAD SUBSURFACE ASSESSMENT

A Dissertation Presented

By

Yifeng Lu

To

The Department of Civil and Environmental Engineering

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in the field of

Interdisciplinary Engineering of Mechanical and Industrial Engineering, Civil and Environmental Engineering

Northeastern University
Boston, Massachusetts

September 2015
ACKNOWLEDGEMENTS

First and foremost, I want to thank my dear advisor Professor Ming L. Wang. It has been an honor to be his Ph.D. student, to work with him, and learn from him. I appreciate all his intelligent guidance, continuous inspiration and support throughout my entire Ph.D. program. The passion and enthusiasm he has for his academics and research were contagious and motivational for me during my pursuit of the Ph.D.. I can hardly express my gratitude for the comprehensive engineering training, wisdom, courage and patience offered by Professor Ming L. Wang.

I am also grateful for my co-advisor Professor J. Gregory McDaniel from Boston University. Prof. McDaniel continually offered ideas and assistance during my long journey in the Ph.D. program. Additionally, I am thankful for my graduate committee: Professor Luca Caracoglia, Professor Sinan Muftu and Professor Rifat Sipahi. Their efforts and interest in my research are highly appreciated.

I would like to thank my colleagues from the Versatile Onboard Traffic Embedded Roaming Sensors Research Center at Northeastern University for their assistance. Working with Dr. Yinghong Cao and Dr. Yi Zhang were especially enjoyable experiences.

Finally, I owe a great debt to my parents and my wife for their understanding, comprehension and love.
## TABLE OF CONTENTS

1. Abstract ...................................................................................................................... xii

2. Introduction ................................................................................................................. 1

   2.1 Motivation of This Research ................................................................................ 1

   2.2 Organization of The Dissertation ......................................................................... 5

3. Essential Elements of Surface Wave Based Methods ................................................. 8

   3.1 The Brief History and Development of Surface Wave Based Methods .......... 8

   3.2 General Principles and Procedures of Surface Wave Based Methods .......... 12

4. Acoustic Radiating Surface Wave ............................................................................. 21

   4.1 From Contact to Non-Contact Sensing by Acoustic Radiating Surface Wave .. 21

   4.2 Challenges for Acoustic Radiating Surface Wave Sensing ............................... 23

   4.3 Modeling of Acoustic Radiating Surface Wave ................................................. 26

   4.4 Implementation of Radiating Surface Waves Sensing ....................................... 63

5. Iterative Wave Number Estimation For Dispersion Curve ....................................... 71

   5.1 Current Dispersion Measurement Methods and Difficulties .............................. 71

   5.2 Iterative Wave Number Estimation Methods ..................................................... 76

6. Inversion of Surface Wave Based Methods .............................................................. 95

   6.1 Brief Review of Current Methods ...................................................................... 95
LIST OF FIGURES

Figure 2-1 The framework of sub-sensors in VOTERS ..................................................... 2

Figure 2-2 VOTERS Van.................................................................................................... 3

Figure 2-3 This huge pothole happened suddenly in ShengZhen, China ......................... 4

Figure 2-4 New pavement construction.............................................................................. 4

Figure 2-5 The prototype of MASS.................................................................................... 5

Figure 3-1 Body wave and Rayleigh wave in uniform half-space (after Bolt, 1976)............ 9

Figure 3-2 The propagations of P-wave, S-wave and Rayleigh wave.............................. 10

Figure 3-3 Diagram of SASW method ............................................................................. 14

Figure 4-1 Acoustic-structural multi-physics coupling .................................................... 22

Figure 4-2 Air-coupled surface wave measurement........................................................ 23

Figure 4-3 Diagram of acoustic waves due to an impact................................................ 24

Figure 4-4 Visualization of the radiating surface wave and direct sound wave by FEM (Lu, 2010) ................................................................................................................................. 25

Figure 4-5 Schematic of a four-layer highway pavement structure................................. 27

Figure 4-6 Meshed geometry with varying element sizes and absorbing layer............... 30

Figure 4-7 Diagram of setting the loss factor for the absorbing layer ........................... 30

Figure 4-8 De-bonding Cases A, B, C and D .................................................................. 32
Figure 4-9 The acoustic pressure wave shape snapshot after 0.8ms by impact for healthy pavement................................................................. 35

Figure 4-10 The snapshot of the elastic solid waves in pavement at 0.125ms after the impact; (a) healthy; (b) Case A; (c) Case C ................................................................. 37

Figure 4-11 Snapshot of elastic stress wave in pavement at 1 ms after impact; (a) healthy; (b) Case B; (c) Case D ................................................................. 38

Figure 4-12 Acoustic pressure comparison in time histories at the pavement surface .... 39

Figure 4-13 Acoustic pressure delay and attenuation from surface to 0.2 m height in air (Case A) ................................................................................................. 39

Figure 4-14 Frequency spectrum comparison; (a) healthy; (b) open-delamination ...... 40

Figure 4-15 Circular impact force on layered half space ...................................... 44

Figure 4-16 Pavement profile as shear velocity ................................................... 50

Figure 4-17 Dispersion curve of the 4-layer pavement model ......................... 51

Figure 4-18 Displacement response along the radial distance from source .......... 52

Figure 4-19 Real part of displacement r-f contour ........................................... 52

Figure 4-20 Planar radiator diagram .................................................................. 54

Figure 4-21 Real part of vertical velocity response r-f contour ......................... 56

Figure 4-22 Radiating surface wave from local surface particle vibration .......... 57
Figure 4-23 (a). Total sound pressure of radiating surface wave field (2cm above the ground); (b). SPL of radiating surface wave field (2cm above the ground).......................... 60

Figure 4-24 (a). The total acoustic pressure by FEA; (b). The radiating surface wave pressure by numerical model (0.2m from impulse; 2cm above ground)..................... 61

Figure 4-25 (a). The total acoustic pressure by FEA; (b). The radiating surface wave pressure by numerical model (0.6m from impulse; 2cm above ground)..................... 61

Figure 4-26 Predicted time history signal of radiating surface wave (2cm above the ground) ........................................................................................................................................... 63

Figure 4-27 Microphone measurement setting up ............................................................ 64

Figure 4-28 Comparison of microphone signal with accelerometer signal. (a) Measured surface acceleration. (b) Measured acoustic above surface signal ...................... 65

Figure 4-29 De-noising sound enclosure for microphone. (a) The schematic design of sound enclosure. (b) Built-up sound enclosure................................................................. 66

Figure 4-30 Effects of the sound enclosure for microphone in noisy environment. (a) Without enclosure. (b) With enclosure ................................................................. 67

Figure 4-31 Ambient noise. (a) Comparison of extracted radiating surface wave and ambient noise. (b) Signal to noise ratio ............................................................................. 68

Figure 4-32 Professional shock accelerometer on the hammer core ................................. 69

Figure 5-1 Phase differences: (a). wrapped; (b). unwrapped......................................... 72

Figure 5-2 Mode jumping at specific frequency............................................................... 73
Figure 5-3 Dispersion curve of dominant mode: (a). Profile 1 in Table 5-1; (b). Profile 2 in Table 5-1. (Ali Zomorodian, et al., 2006) ................................................................. 75

Figure 5-4 Testing configuration ............................................................................. 77

Figure 5-5 Flow chart of the complex wave number estimation method ............... 80

Figure 5-6 Diagram of simulated test for Cases 1 ~ 5 ........................................... 81

Figure 5-7 Contour of NMSE versus real and imaginary parts of wave numbers ...... 82

Figure 5-8 (a) Estimated real part of wave number for Case 1 (b) imaginary part of wave number (c) NMSE ......................................................................................... 83

Figure 5-9 (a) Dispersion curve for Case 1 (b) real part of wave number .............. 85

Figure 5-10 (a) Empirical inversion by acoustic pressure signal (b) real part of wave number comparison ....................................................................................... 86

Figure 5-11 (a) Dispersion curve comparison (b) empirical inversion (acceleration)..... 88

Figure 5-12 (a) Normalized ratio: Im(k)/Re(k) (b) empirical inversion (acoustic pressure) ..................................................................................................................... 89

Figure 5-13 Imaginary part of wave number dispersion (Case 4) ............................ 90

Figure 5-14 Empirical inversion (Case 5) ................................................................ 91

Figure 5-15 Test configuration at NCAT and pavement profile as design .............. 92

Figure 5-16 (a) Dispersion curve (b) imaginary part of wave number (c) normalized ratio: Im(k)/Re(k) by acceleration (d) normalized ratio: Im(k)/Re(k) by acoustic pressure ..... 94
Figure 6-1 Distribution of particle displacement along with penetrating depth of surface wave ................................................................. 99

Figure 6-2 Flowchart of fast inversion analysis .......................................................... 102

Figure 6-3 Analytical dispersion curve (dominant mode) ......................................... 104

Figure 6-4 Inverted shear velocity profile vs. original profile for ascending stiffness profile ................................................................. 105

Figure 6-5 Inverted shear velocity profile vs. original profile for descending stiffness profile ................................................................. 106

Figure 6-6 Estimated shear velocity profiles using the proposed inversion algorithm... 107

Figure 6-7 Layered pavement model and free plate model of stiff top layer .......... 109

Figure 6-8 Three-layered pavement model with stiff top layer ............................ 109

Figure 6-9 Pavement dispersion fitting inversion by Lamb wave modes .............. 110

Figure 6-10 Inversion results of above pavement model ....................................... 111

Figure 7-1 Early version of MASS design ............................................................. 113

Figure 7-2 Field test with early version of MASS ................................................ 114

Figure 7-3 Integration of hardware of MASS .......................................................... 114

Figure 7-4 DAQ communication architecture ....................................................... 115

Figure 7-5 EM hammer unit .................................................................................. 116

Figure 7-6 Hammer control unit .......................................................................... 117
Figure 7-7 Automatic operation by distance trigger .......................................................... 118

Figure 7-8 Software integration architecture ..................................................................... 119

Figure 7-9 Test on asphalt pavement. (a) Mobile sensing with MASS. (b) Test configuration .............................................................................................................................. 120

Figure 7-10 Testing on asphalt pavement. (a) Extracted radiating surface wave. (b) Estimated elastic modulus profile ......................................................................................... 121

Figure 7-11 Concrete slab test configuration. (a) Test set-up. (b) Slab cross-section profile .............................................................................................................................. 122

Figure 7-12 Concrete slab test results. (a) Extracted radiating surface wave. (b) Estimated elastic modulus profile ......................................................................................... 123

Figure 7-13 Pingree bridge deck test (Rowley, MA). (a) Scanning path on bridge deck. (b) MASS operation on bridge deck ..................................................................................... 124

Figure 7-14 Pingree bridge deck test results. (a) Extracted radiating surface wave. (b) Joint crack. (c) Continuous scanning results ........................................................................... 125

Figure 8-1 Schematic of tire loading model ................................................................. 127

Figure 8-2 Coordinates of source and receiver positions.............................................. 129

Figure 8-3 Underbody sound image ............................................................................... 129

Figure 8-4 Acoustic wave field from tire loading (2009 Toyota Prius with mass 0.005g (1% of speed bump acceleration)) ............................................................................. 130

Figure 8-5 Acoustic data ingredient from tire-pavement noise .................................... 132
Figure 8-6 Tire-pavement subsurface acoustic radiating sketch................................. 133

Figure 8-7 Impact-echo with HHT to extract surface wave ........................................... 136

Figure 8-8 HHT based surface wave identification from vehicle running impact ........ 137

Figure 8-9 Typical example for HHT decomposition..................................................... 138

Figure 8-10 Sound pressure spectrum............................................................................. 139

Figure 8-11 Normalized energy in each mode................................................................. 140

Figure 8-12 Frequency-time distribution within 100Hz................................................ 141

Figure 8-13 Comparison of normalized mode energy proportion................................. 142

Figure 8-14 Normalized mode energy proportion distributions for three runs (Blue: healthy pavement; Green: pavement with debonding)......................................................... 143
LIST OF TABLES

Table 4-1 Energy ratio of elastic waves (after Richart, et al., 1970) ................................ 21
Table 4-2 Asphalt concrete highway pavement profile parameters .................................. 29
Table 4-3 4-layer pavement model profile ........................................................................ 50
Table 5-1 Two typical profiles (Ali Zomorodian, et al., 2006) ........................................ 74
Table 5-2 Acoustic-Structural half space .......................................................................... 81
Table 5-3 Profile of fluid half-space coupled with layered solid half-space ................. 87
Table 5-4 Profile of pavement segment as design ............................................................ 92
Table 6-1 Layered structure with ascending velocity profile ......................................... 103
Table 6-2 Layered structure with descending velocity profile ....................................... 105
Table 8-1 Pavement model profile .................................................................................. 130
Table 8-2 Properties of the HHT .................................................................................... 135
Table 8-3 Criteria for surface wave characteristics ......................................................... 136
Efficient and economical solutions for monitoring the conditions of transportation infrastructure are in urgent and critical demand in United States. The current state of road and bridge network health of United States has fallen into disturbing circumstances according to recent report cards administered by the American Society of Civil Engineering (ASCE). In 2013, road conditions scored a D and bridges received a grade of C+. The national transportation infrastructure conditions affect not only the lives of average people utilizing roadways, but also the economic efficiency and security of the country. Efforts to monitor the health of transportation infrastructure include examinations of both surface and subsurface levels. Diagnosing problems at the subsurface level is equally as vital for transportation infrastructure as identifying surface level issues. One major technique used to study the state of subsurface infrastructure is the surface wave method which uses mechanical vibration measurements nondestructively. The subsurface profile information, such as stiffness and layer thickness, is measured from the dispersion characteristics of the ground by exciting surface waves and then picking up their vibration responses. The limitations of using conventional surface wave methods include the low testing efficiency due to ground attached contact sensing, the uncertainty of dispersion caused by phase unwrapping, difficulty and mode jumping, and the slow inversion that is caused by iterative trial-checks with forward analysis. In order to overcome these limitations and improve surface wave based methods, this dissertation develops a prototype of a mobile acoustic subsurface sensing system which uses microphones to sense radiating surface waves in a
non-contact way. To verify the feasibility of using microphones instead of ground attached accelerometer or geophone to measure radiating surface waves, a full-scale high-resolution air-coupled pavement finite element (FE) model was established. It indicated that the radiating surface waves and ground surface waves both relay the same subsurface information. The acoustic pressure level of radiating surface wave allows the sensing with microphone, and the arrival time of radiating surface wave could be separated from the direct sound wave due to the significant wave speed difference. The FEM offers an intuitive visualization of the radiating surface wave above the pavement, but the computing time is a limitation. For more efficient forecasts of acoustic radiating surface waves above the road, a numerical model is built-up based on stiffness matrix and particle acoustic radiation principles. The acoustic surface wave field can be predicted with parametric studies, including examinations of the impulse magnitude and frequency features, impactor contact area, ground profile information and virtual sensing location. The FEM computing time of hours-days is reduced to minutes when using the numerical model. Based on these foundations, dispersion curve analysis, which is the critical prerequisite of subsurface profiling, is followed with a proposal of a wave number fitting method. The wave number fitting method achieves more accurate dispersion features with sparse measurement channels. For the inversion analysis, this research develops a fast inversion algorithm based on the in-situ particle displacement distribution of fundamental wave modes. The inversion procedure could be shortened dramatically without tedious trial-error iteration. For subsurface profile with a considerably stiff top layer, the fundamental wave mode would jump as Lamb waves with A0 dominant mode. In this case, a Lamb wave based inversion algorithm is developed to resolve the irregular profile by tracing the A0 Lamb wave mode
with measured dominant modes. To implement the integrated mobile acoustic subsurface sensing (MASS), a prototype hardware platform was constructed. It was developed on a three-wheeled cart with an automatic electromagnetic impulse hammer, a DAQ system, distance trigger and directional microphones. Both mechanical sound enclosures and numerical signal filers were designed to improve the signal to noise ratio for field tests. Field tests were conducted to demonstrate the capability of the MASS prototype. Additionally, studies on the tire excited elastodynamic response sensing of pavement are also discussed for the sake of implementing the subsurface characterization even more efficiently through driving a regular vehicle.

**Keywords:** surface wave, acoustic radiating, mobile sensing, microphone, dispersion, inversion, MASS.
2 INTRODUCTION

2.1 Motivation of This Research

According to the official report card of American Society of Civil Engineering (ASCE 2013), the grades of the road and bridge networks in United States are not in good condition. In 2013, roads received a D grade and bridges scored a C+. These worrisome conditions should motivate urgent reparations for transportation infrastructure in United States. The current conditions of the road and bridge networks cause unpleasant experiences but also incur grave economic costs. Moreover, the deterioration of the transportation infrastructure jeopardizes the lives of average passengers. Efficient health diagnosis and maintenance of the transportation infrastructure is vital to addressing this nationwide challenge.

Versatile Onboard Traffic Embedded Roaming Sensors (VOTERS) Research Center at Northeastern University has researched and tested a variety of solutions. The VOTERS project focuses on providing a simple and inexpensive, yet highly efficient technology to detect surface and subsurface trouble spots with minimal to no disturbance of traffic patterns. This versatile sensors system is an intelligent combination of multiple sensors: acoustic sensors, millimeter wave radars, gigahertz electro-magnetic array and an optical profilometry camera. Fused data from these sensors supplies adequate parameters of the road conditions to policy and decision makers in a mobile and real-time fashion. (Birken, et al. 2012).
There are two levels of sensing in the VOTERS project. Level one is dedicated to road surface health assessment and utilizes sub-sensors including: **SLiMR** (Surface Looking Millimeter-wave Radar), **SOPRA** (Surface Optical Profilometry Roadway Analysis) and **TEASe** (Tire Excited Acoustic Sensing). Level two is dedicated to road subsurface health assessment, utilizes sub-sensors, including **GEARS** (Gigahertz Electro-magnetic Array Roaming Sensors) and **TEASe** (Tire Excited Acoustic Sensing) sub-sensors. Fig. 2-1 presents the framework of the sub-sensors VOTERS uses. All the sensors' data are fused into a **MAP** (Management And Prognosis) system to express the analyzed results of road health assessment corresponding to the actual road network map. Most of the sub-sensors are integrated into a regular vehicle platform, the VOTERS Van, which is shown in Fig. 2-2. The sensing signal is taken while the VOTERS Van operates at a regular speed in the natural traffic environment.

![Figure 2-1 The framework of sub-sensors in VOTERS](image-url)
As mentioned above, VOTERS is dedicated to not only the road surface health assessment (potholes, manholes, cracks, micro-textures, raveling, rutting and so on) but also the road subsurface health assessment. Subsurface health conditions are highly critical to the transportation infrastructure health monitoring and maintenance. These subsurface conditions are hidden and can not be easily inspected but they could be extremely dangerous and cause accidents without any warning. Deterioration such as potholes and cracks can develop from subsurface defects. Fig. 2-3 is an image of a real accident that happened in Shengzhen, China, in May of 2013. This huge pothole appeared suddenly, causing many deaths, with no warning since the defect was hidden beneath a nice looking road surface. When routine inspections are conducted on a regular basis, potential dangers can be identified immediately. Additionally, new pavement construction is a costly investment for the investigator (Fig. 2-4). The quality authentication of the construction becomes a primary task to verify the confidence of the investigator. Subsurface inspection would allow investigators to look underneath surface-level conditions.
In the VOTERS project, MASS (Mobile Acoustic Subsurface Sensing) is an important sub-system which addresses the above challenges through utilizing acoustics in a subsurface sensing method (Fig. 2-5). Belonging to sub-sensors system of TEASe, MASS provides
an intermediate product from a 3-wheeled pushing cart to regular vehicle-equipped acoustic sensing system.

![The prototype of MASS](image)

**Figure 2-5 The prototype of MASS**

The MASS system is intended to be fast and non-contact, independent and mobile. More details of the mechanism of MASS system will be introduced in consequent chapters.

### 2.2 Organization of The Dissertation

This dissertation is organized into six topics and each has a dedicated chapter. Chapter 3 summarizes the essential fundamental knowledge of surface wave based methods. It introduces the development history of surface wave based methods and then introduces popular methods such as SASW (Spectral Analysis of Surface Waves), MASW (Multichannel Analysis of Surface Waves), \( f-k \) (Frequency and Wave number) and Lamb wave methods. This chapter sets up the essential background information for the readers so that the following Chapters flow sequentially.
Chapter 4 presents the acoustic radiating surface wave method, which is also called the air-coupled surface wave. This chapter summarizes the physical modeling of pavement as layered half space. The objective of the non-contact sensing methods utilized in MASS inspired the study of the acoustic radiating surface wave method, which is a result of acoustic-structure interaction. The FEM model and numerical simulation model were built up to confirm the concept and predict the wave field for both surface displacement and radiating acoustic waves. Also, the acoustic signal processing strategy has been discussed to prepare the MASS for the noisy field test.

Chapter 5 is on the topic of dispersion measurement methods. The surface waves would disperse if the media are layered with different wave velocity properties. This dispersion corresponds to the frequency and wavelength brings the information of subsurface profile. Chapter 5 reviews popular existing methods and then proposes an iterative wave number fitting method to get the dispersion curve with better accuracy.

Chapter 6 focuses on the inversion problem of the surface wave as well as the acoustic radiating surface wave. Inversion is the most important procedure of subsurface sensing since it back-calculates the layered profile which results in the measured dispersion curve. In situ particle displacement, distribution based fast inversion was proposed for regular profile, and Lamb wave based inversion was proposed for profile with stiff top layer.

Chapter 7 is a summary of the implementation of the theories discussed in aforesaid chapters. It introduces the development of the hardware and software prototypes as MASS. Typical field tests have been conducted and analyzed.
Chapter 8 discusses the opportunities of using tire excited elastic waves to inspect subsurface conditions. This chapter proposes an elastic plate based pavement model to estimate the tire loading effects on ground. Then a HHT (Hilbert-Huang Transform) based method is proposed to identify debonding underneath the pavement with identical surface texture through the NCAT test.

Chapter 9 concludes the findings and summarizes recommendations for future work.
3 ESSENTIAL ELEMENTS OF SURFACE WAVE BASED METHODS

This chapter briefly reviews the fundamental backgrounds and physics of surface wave methods, which are the foundations for our research.

3.1 The Brief History and Development of Surface Wave Based Methods

Before the surface wave methods can be applied, traditional near surface explorations usually require boring, sampling and penetration testing. All these traditional testing methodologies have to manipulate the ground with destructive treatments, somewhat with the objectives of stress wave speed profiling geophysical sets. The typical body wave as compression and shear wave and surface wave (Rayleigh wave) are diagramed in Fig. 3-1. Among the stress waves, shear wave velocity ($V_S$) is of special interest since it is a key parameter in both soil dynamics, near-surface exploration and geotechnical earthquake engineering (Stokoe, et. al., 2004).

The early intrusive methodologies started in the 1960s and the most popular methods were the Crosshole method, Downhole method, Seismic cone penetrometer method and Suspension logging method. The Crosshole method applies active source and receivers arranged in the same depth in the borehole to measure the compression (P) and shear wave velocities. The profiling depth depends on the depth of the source receiver in the borehole. Downhole method is similar to Crosshole method but reduces the borehole number to only
one and sets exciting source on the surface. Seismic cone penetrometer method uses a penetrating probe with tip and side resistance sensors to measure the properties along the layers as it descends. It also measure the Shear Horizontal (SH) velocity through embedded horizontal impact. Suspension logging method uses several different sensors to measure the radiation, magnetic and stiffness properties of the soil. The propagation styles of P-wave, S-wave and Rayleigh wave are summarized in Fig. 3-2.

![Figure 3-1](image.png)

Figure 3-1 Body wave and Rayleigh wave in uniform half-space (after Bolt, 1976)
Surface wave methods do not ruin the ground when sampling and were the main field seismic method used until recently. Interests in surface wave and related models (e.g. acoustic radiating surface wave) keeps rising due to their convenience and nondestructive nature. All surface wave propagations are along a free surface or interface between differing media and the energy is carried on the near-surface. Typical surface waves are Rayleigh waves, Love waves, Stoneley waves and Scholte waves.

Rayleigh waves are the most interesting surface acoustic waves (SAW) for nondestructive testing since they travel in both longitudinal and transversal directions and are easily measurable. As Fig. 3-1(c) presented, Rayleigh waves’ longitudinal and transversal propagation style make the in-situ particle motion ellipses in planes normal to the surface and parallel to the direction of propagation. The ellipse motion performs retrograde on the surface and at shallow depths, but after passing an inflexion depth, the ellipse motion becomes prograde at deeper depths. For most of the Rayleigh wave based method, the measurement focus is on the vertical motion of particles on the free surface. Strictly speaking, Rayleigh waves are defined within a vacuum half space. However, when the top
or shallow layers have dramatic variants of stiffness (shear velocity $V_s$) with sub-grade half space, the Rayleigh wave would trapped in the shallow layers as guided waves, which instead performs as a Lamb wave. According to this reason, in layered half space, Rayleigh waves are coupled with Lamb waves and defined as Rayleigh-Lamb waves.

Love waves (also known as Q waves) are the surface waves whose propagation is only in a transversal style. They are the result of SH (Shear Horizontal) waves trapped in the surface layers. Since they only perform on the horizontal (transversal) style, Love waves are not studied as much as Rayleigh waves. Stoneley waves (leaky Rayleigh waves) are the surface waves propagates along a solid-solid interface. When it leaks between a liquid-solid interface, it converts to a Scholte wave, which is commonly used in liquid-filled borehole tests.

Among these typical surface waves, Rayleigh waves and Rayleigh-Lamb waves are critically important for the road NDT. Usually, when there is a vertical point of impact, such as a hammer on the ground, Rayleigh waves are excited and propagate at a speed slightly slower than the Shear Velocity. The relationship between P-waves, S-waves and Rayleigh waves is expressed in Eq. 3.1.1~3.1.4.

\[
V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E(1-v)}{\rho(1-2v)(1+v)}}, \quad (3.1.1)
\]

\[
V_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2\rho(1+v)}}, \quad (3.1.2)
\]
The velocities are defined by the material properties such as density $\rho$, Poisson ratio $\nu$ and elastic modulus $E$. Rayleigh wave velocity depends on the Poisson ratio of the material. For a homogenous infinite half space, Rayleigh wave velocity could be calculated with the bi-cubic equation expressed in Eq. 3.1.5. However, for complicated half space structure as layered half space, there is no direct solution as analytical closed answer. More complex calculation methods for calculating Rayleigh wave speed are realized through layer assembly methods with continuous interface features. This part will be discussed in Chapter 4.

$$\frac{V_S}{V_P} = \sqrt{\frac{1 - 2\nu}{2(1 - \nu)}}$$  \hspace{1cm} (3.1.3)$$

$$\frac{V_R}{V_S} \approx \frac{0.87 + 1.12\nu}{1 + \nu}$$  \hspace{1cm} (3.1.4)$$

3.2 General Principles and Procedures of Surface Wave Based Methods

3.2.1 SASW method

The most typical surface wave method with sparse sensing channels is the SASW method. SASW is a significant improvement from its predecessor, the Continuous Surface Wave (CSW) method. The CSW method utilizes a vibrator in a fixed frequency to excite the surface waves. Consequently, in order to measure the surface wave feature in a frequency
range, a substantial amount of separate frequencies has to be operated to measure the response of the ground of every frequency. By this way, the dispersion property that the measured phase velocity varying with frequency could be accessed.

Compared to intrusive methods for subsurface inspection, the CSW method utilizes nondestructive testing and is admired by geophysical and seismic engineers. The shortness of CSW is the requirement of sweeping the frequency one to one in a low efficiency.

Based on the principles of the CSW method, the Spectral Analysis of Surface Waves (SASW) made great advances in operation efficiency. Instead of testing with fixed frequency from one to another, SASW employs the spectral feature of a sharp and clear transient impact to excite a broad band frequency response. Ideally, only one strike would supply the dispersion feature corresponding to the whole frequency range of interests. If two sensing channels are given to record the time history signal of the ground vibration, the phase angles with respect to the frequency of the two channels ($\phi_1(f), \phi_2(f)$) would be obtained by Fast Fourier Transform (FFT) as shown in Fig. 3-3(a). Then phase difference between the two channels $\Delta\phi(f) = \phi_1(f) - \phi_2(f)$ could be known as Fig. 3-3(b). $D_2$ is the arranged space between two channels, the phase velocity with respect to frequency could be calculated as $V_R(f) = 2\pi f D_2/\Delta\phi(f)$, which is the dispersion curve telling the subsurface profile characteristics such as in Fig. 3-3(c). The dispersion curve could be converted in the form of phase velocity with respect to wavelength, through $f = V_R/\lambda$. Finally, inversion analysis would be applied to get the shear velocity profile $V_S$ to determine the layered structure for both thickness and stiffness.

Although SASW application is popular, it still has several drawbacks: a). it only measures the apparent surface wave mode, higher mode inclusion is underestimated; b). there are
phase angle unwrapping difficulties (Al-Hunaidi, 1992); c). it requires expertise initialization for back-calculation; d). there are inversion difficulties on non-regular profiles, such as pavement; e). it uses ground-mounted sensing.

Figure 3-3 Diagram of SASW method

3.2.2 MASW method

Motivated by the limitations of the SASW method that are mentioned above, Park, et al. (1998) proposed a surface wave method which uses multiple sensing channels instead of two channels. It was termed MASW (Multichannel Analysis of Surface Waves). Park proposed a Phase-Shift method to improve the resolution of dispersion contour image compared to Slant Stack (also called pi-omega) method.

The general procedure of MASW includes:

(1). A multi-channel field record diagram is converted into frequency domain by Fast Fourier Transformation (FFT) and the individual frequency component is got;
(2). then the amplitude of each frequency component is normalized with respect to each frequency's max amplitude;

(3). the decomposition and normalization, a sweep of phase velocity would be applied for a frequency, necessary amount of phase shifts are calculated to compensate for the time delay corresponding to a specific offset. All of them are summed together to make a summed energy, all summed energy in frequency-phase velocity coordinates would be present the pattern of energy accumulation of dispersion contour image;

(4). finally, the superposed dispersion contour image is accessed when the field record has a multi-modal of waves.

One benefit of this method is that it maximizes the S/N ratio during the data acquisition and subsequent processing steps through a linear separation of each Rayleigh wave frequency component. This allows calculation of phase velocities by simply measuring the linear slope of each frequency component (Park, et al., 1999). Nonetheless, it also requires a number of sensing channels to realize high levels of redundancy with a single field configuration.

Recently, more applications of the MASW method with nonlinear sensing array are also utilized with either active or passive impact source for road foundation testing (Park, et al., 2007, 2008). These strategies deploy a circular sensor array to measure either the active impact source by the operator or the passive impact source by the heavy passing vehicles on the road.

3.2.3 f-k method
f-k (Frequency-Wave number) method is another multi-channel sensing method. It has been widely used first in the geophysical area, and more recently in geotechnical engineering and near-source testing applications. The early researchers as McMechan, et al., (1981) transfer recorded multi-channeled time-offset diagram in frequency-wave number domain by means of a 2-D FFT or slant-stack analysis. Eq. 3.2.3.1 indicates the relationship between the time-offset $V(x,t)$ and the dispersion relationship $D(k,w)$ where $N(k,w)$ is the source property in the frequency-wave number domain. With the slant stack method and Fourier transfer, Eq. 3.2.3.1 could be finalized as Eq. 3.2.3.2, which connects the dispersion curves with the wave field.

$$V(x,t) = \int dk \int dw e^{i(kx-wt)} \frac{N(k,w)}{D(k,w)} \quad (3.2.3.1)$$

$$U(p,\omega) = \frac{N(\omega p,\omega)}{D(\omega p,\omega)} \quad (3.2.3.2)$$

Alternatively, a 2D FFT could gain the same transfer from the time-offset domain to the frequency-wave number domain as Eq. 3.2.3.3, where $U(f,k)$ is the transferred wave field in frequency and wave number domain.

$$U(f,k) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} V(x,t) e^{-i2\pi(f-kx)} dt dx \quad (3.2.3.3)$$

The f-k method processing procedure seems easier than the MASW method, however, it usually requires more sensing channels, up to 128, or even 256 receivers. Therefore, the sensing resolution may be not as high as MASW if the same number of receivers are used.
Both the MASW and f-k methods are capable of measuring not only the fundamental mode but also the higher modes in a global property in the receiver-spread area (Stokoe, *et al.*, 2004).

### 3.2.4 Lamb Wave method

Different from the three typical methods of surface waves listed above, the Lamb wave method is rarely used in geophysical or geotechnical engineering because Rayleigh waves, especially the fundamental wave mode, is predominant in geophysical sites with regular profiles. Instead, Lamb waves are popular in composite material NDT, such as wings of planes and thin metal plates.

Ryden *et al.* (2004) studied the surface wave properties on flexible pavement which has an irregular profile (from stiff to soft, with depth or having soft layers embedded in stiff layers). Ryden explained the special observations of the surface wave methods on typical pavement when there exists a stiff top layer and the stiffness decreases with depth. According to Ryden's study, the dominant measurement of surface waves on a pavement (irregular profile with stiff top layers) is leaky quasi-Lamb waves in the top and second pavement layers. Also, the fundamental antisymmetric mode of vibration (A0) is the predominating mode occurring in the stiff top layer. The mode jumping from fundamental mode to higher modes are found coinciding with the A0 mode as the main dispersion branch. This explanation was verified by both field surface wave measurement and the theoretical analysis by a dispersion study software (*Disperse*). Then systematically, Ryden's study answered the confusions of failure and difficulties when the traditional surface wave methods were employed on the pavement structure. Ryden's findings initiated serious analysis of the surface wave method for pavement. He proposed that the leaky Lamb wave,
or more generally the Rayleigh-Lamb wave, should be used for pavement-like layered structures, rather than the Rayleigh wave.

For solid plate with traction-free boundaries, the excited waves are guided in the layers within the plate, resulting from interference of multiple reflections and mode conversion of longitudinal and shear waves. In addition, they are called Rayleigh-Lamb waves. For a specific thickness, the harmonic guided waves in the plane of the plate would exist only for some combinations of frequency-phase velocity due to the standing waves in the plate thickness. These pairs of frequency and phase velocity form the groups of dispersion curves for Rayleigh-Lamb waves. Since the dispersion curves depend on the standing waves in the thickness, the governing equations of dispersion curves are related to the material properties and thickness of the plate. For NDT applications, usually only the longitudinal and flexural waves are of intensive interests while the third wave, such as horizontally polarized shear waves, are not used.

The longitudinal waves are alternatively called symmetric waves (S mode) and obey the following mode equation (Eq. 3.2.4.1).

\[
\frac{\tan \beta \frac{d}{2}}{\tan \alpha \frac{d}{2}} = -\frac{4\alpha \beta k^2}{(k^2 - \beta^2)^2}
\]  

(3.2.4.1)

where

\[
\alpha^2 = \frac{\omega^2}{C_L^2} - k^2
\]

(3.2.4.2)
\[ \beta^2 = \frac{\omega^2}{C_T^2} - k^2 \]  

(3.2.4.3)

\( d \) is the plate thickness, \( k \) is the wave number, \( C_L \) is the longitudinal wave velocity, and \( C_T \) is the shear wave velocity. The phase velocity would be \( c = \frac{\omega}{k} \).

The flexural waves are alternatively called antisymmetric waves (A mode) and obey the following mode equation (Eq. 3.2.4.4).

\[
\frac{\tan \beta \frac{d}{2}}{\tan \alpha \frac{d}{2}} = -\frac{(k^2 - \beta^2)^2}{4 \alpha \beta k^2}
\]

(3.2.4.4)

For numerical computation, the SYM (Symmetric Mode equation) and ASYM (Antisymmetric Mode equation) are commonly used for Rayleigh-Lamb wave dispersion curves (Eq. 3.2.4.5; 3.2.4.6). They are Trigonometric transform and power expansion of governing equations.

\[
(k^2 - \beta^2)^2 \cos \alpha \frac{d}{2} \sin \beta \frac{d}{2} + 4k^2 \alpha \beta \sin \alpha \frac{d}{2} \cos \beta \frac{d}{2} = 0
\]

(3.2.4.5)

\[
(k^2 - \beta^2)^2 \sin \alpha \frac{d}{2} \cos \beta \frac{d}{2} + 4k^2 \alpha \beta \cos \alpha \frac{d}{2} \sin \beta \frac{d}{2} = 0
\]

(3.2.4.6)

Rogers (1995) studied a typical dispersion curves group. Accordingly, it could be learned the antisymmetric and symmetric modes exist in turn. Only the fundamental antisymmetric and symmetric modes (A0 and S0) span the whole frequency range while all higher
antisymmetric and symmetric modes only permissible for a frequency range as cutting-off frequencies. Additionally, the dispersion curves demonstrate some critical limitations when the product of frequency and thickness closed to zero. The limits are summarized in Eq. 3.2.4.7 and 3.2.4.8 for symmetric and antisymmetric modes respectively. The limit of Eq. 3.2.4.7 is called plate wave speed. One more interesting property of Lamb wave is in the limit of high frequency and large plate thickness, the phase velocity of both the symmetric and antisymmetric zero order modes approach the Rayleigh wave speed $C_R$, and for all non-zero order modes, $c$ approaches the shear wave velocity $C_T$. They are embedded in two limits of $C_R$ and $C_T$.

\[
\lim_{f \to \infty} C_s = \sqrt{\frac{E}{\rho(1-\nu^2)}} \quad (3.2.4.7)
\]

\[
\lim_{f \to \infty} C_d = \sqrt[4]{\frac{E}{3\rho(1-\nu^2)}} \sqrt{\omega d} \quad (3.2.4.8)
\]

Discussion

This chapter summarized the essential physics and general processing methodologies of surface waves, Rayleigh waves and Rayleigh-Lamb waves. The variant strategies own diverse mathematical handling and measurement manners, however, they all share the identical physical foundation of surface waves. The acoustic radiating surface wave is an air-coupled result from ground surface waves (or Rayleigh waves, Rayleigh-Lamb waves) propagating. Thus, understanding the physics and analysis methods of ground surface waves is necessary for the following acoustic radiating surface wave processing.
4 ACOUSTIC RADIATING SURFACE WAVE

4.1 From Contact to Non-Contact Sensing by Acoustic Radiating Surface Wave

The efficiency of surface wave sensing is always a critical concern for NDT for ground and pavement. Surface waves compared with the body waves (P-waves and S-waves) have the following advantages:

(1). Easy to excite from the ground surface NDT;

(2). Brings the most important subsurface profiling information with dispersion curves;

(3). Attenuates slowly respect to the distance from source (Rayleigh wave attenuates proportional to $r^{-1}$);

(4). Owns the main energy of elastic waves (Table 4-1).

<table>
<thead>
<tr>
<th>Wave type</th>
<th>Percent of total energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-wave</td>
<td>7</td>
</tr>
<tr>
<td>S-wave</td>
<td>26</td>
</tr>
<tr>
<td>Surface wave</td>
<td>67</td>
</tr>
</tbody>
</table>
According to these advantages, the Rayleigh wave is an ideal candidate to study subsurface profiling. Moreover, the acoustic-structural multi-physics coupling makes the attractive potential for acoustic radiating of surface wave becoming a new trend. When vibrations of the ground surface occur, the accelerations of all the in-situ particles would be continuous on the interface between the structural ground solid and the acoustic air. The interface particles radiate the air-coupled surface wave into the air domain as an acoustic radiating surface wave. This acoustic-structural multi-physics coupling is indicated as Fig. 4-1.

![Figure 4-1 Acoustic-structural multi-physics coupling](image)

The radiating surface wave is coupled with the surface acceleration and the effects from the fluid as the pressure force is loading back to the ground solid. For air-pavement coupling, the pressure force from the air influencing the ground could be ignored. This assumption is based on the numerical simulation on the subsequent sections.

Based on the understanding of physics, non-contact sensing with microphone in the air domain has become the trend for surface wave NDT. The theoretical study and corresponding applications of acoustic radiating surface wave (air-coupled Rayleigh wave)
was discussed by Zhu (2005). Consequently, the air-coupled SASW and air-coupled impact-echo methods have been developed. Typical examples include Zhu's research on air-coupled SASW, air-coupled MASW, air-coupled impact-echo (Zhu, 2005), and Ryden's (2007) research on the rolling microphone array sensing. Fig. 4-2 presents an air-coupled surface wave field testing.

![Air-coupled surface wave measurement](image)

**Figure 4-2 Air-coupled surface wave measurement**

### 4.2 Challenges for Acoustic Radiating Surface Wave Sensing

Although the attractive potential of acoustic radiating sensing led the trend of non-contact sensing for surface wave, the natural difficulties arose at the same time. On one hand, the acoustic radiating surface wave is not alone in the air domain when it is excited with some kind of impact source. When an impact source is applied, the area of the impact contact would vibrate heavily and radiate out a direct sound wave as a monopole sound source. This direct sound wave propagates in a spherical wavefront with a relatively strong amplitude, which may contaminate the wanted acoustic radiating surface wave if the two waves are not separated.
On the other hand, besides the unwanted noise from the direct sound wave, there are other minor body waves from the same impact. Zhu et al., (2005), studied a surface wave between water and solid coupling. It was found that the P-and S-waves would arrive before the leaky Rayleigh wave. The P-wave arrives fastest, while S-wave arrives slightly before than leaky Rayleigh wave. The P-wave is relatively easy to remove since it arrives well before the other waves. However, when the receiver is too close to the source, the S-wave and leaky Rayleigh wave do not have appropriate separation, which makes extracting a clean Rayleigh wave somewhat difficult. One more wave, the Scholte wave, which is the leaky surface wave from solid to liquid, appears as well. For air-pavement coupling, the Scholte wave will converge with the leaky Rayleigh wave.

Without considering the other ambient acoustic noise, the diagram of the acoustic waves are presented in Fig. 4-3.

![Diagram of acoustic waves due to an impact](image)

**Figure 4-3** Diagram of acoustic waves due to an impact

Through FEM analysis, the acoustic wave field above the layered pavement after a vertical point impact is demonstrated by Fig. 4-4. It could be found that the radiating surface wave
Northeastern University | 25

propagates faster than the direct sound wave. The radiating surface wave is approximated as a plane wave that is tangent to the spherical direct sound wave on the hemisphere's front top. The tangent point forms a small angle from the vertical direction – the Rayleigh angle. The larger the difference between the wave speeds of the two coupled materials, the smaller Rayleigh angle would be as Eq. 4.2.1.

\[
\theta = \sin^{-1}\left(\frac{V_d}{V_R}\right)
\]  

(4.2.1)

where \(V_d\) is the sound velocity and \(V_R\) is the Rayleigh wave speed.

Figure 4-4 Visualization of the radiating surface wave and direct sound wave by FEM (Lu, 2010)

In addition to the excited air-coupled P-wave, S-wave, radiating surface wave, and direct sound wave, there are other sources of ambient noise (traffic, wind, etc.). As a result, the task of sensing the radiating surface wave turns into a challenge for air-coupled expansion. The noise reduction in the field test environment is a key pre-processing step for all the
subsequent signal processing. The specific implementation would be discussed in section 4.4 of this chapter.

4.3 Modeling of Acoustic Radiating Surface Wave

4.3.1 FEM Modeling of Pavement Structure and Its Acoustic Radiating

The forward modeling of a pavement structure could be realized through numerical methods. However, there is no analytical closed-form solutions could capture the arbitrarily complicated geometry with defects and complex material parameters. In order to predict the acoustic radiating above the pavement structure and study the feasibility and effects of different subsurface defects, a FE model was developed with commercial FEM software COMSOL Multiphysics 3.5a.

Finite element methods have been used in material and structural NDT for decades. However, until recently, a majority of FEM has been limited to simple models of uniform materials (including defects) in only one physical domain. In this model, a stratified pavement model, which had three layers of different material properties upon a half-space, was created to describe the regular highway pavement structure, as shown in Fig 4-5. Meanwhile, the model realized multiple-physics field coupling, which included both structural dynamics domain and air fluid-mechanics domain. Thanks to the effective coupling at the air-structure interface, the acoustic signal above the pavement surface caused by radiating Rayleigh wave could be identified clearly and used to detect subsurface de-bonding defects.
For the de-bonding defects in the model, two main situations were modeled and computed – with assignments of two typical relative locations with respect to the impact sources. The first type of de-bonding was defined as open de-bonding, while the other type was closed de-bonding which will be discussed in detail later, respectively. Moreover, in order to understand the fundamental progress of interaction of the air-coupled radiating Rayleigh wave with de-bonding, the FEA simulation was chosen to use time history transient analysis. In contrast to direct frequency analysis, a transient analysis is more time consuming, thus, the model is pre-optimized in order to solve the problem within an acceptable size. In addition, post-FFT processing of the temporal results was introduced to look for insight into the frequency spectrum.

1. Computing task reduction

To simulate a radiating Rayleigh wave in highway pavement structure is challenging due to the infinite field effects and the high-resolution mesh size required to be able to observe the wave itself. The domains of interest have radii of 3m for the high resolution portion and 10m radii for the outer compensation and absorbing layer, respectively.
Both a 3D model and a 2D rotationally symmetric model were created and simulated. The excitation source was set as a vertically loaded point force to give a short, but sharp impact to the pavement surface – allowing the 3D model to be simplified to a 2D rotationally symmetric model. Without sacrificing the 3D characteristics, a 2D rotationally symmetric model was an advisable choice since the symmetric axis is aligned with direction of the loading force.

(2) Element mesh size

The element mesh size is an important parameter to consider. An improper element size (either too large or too small) could weaken the effectiveness of the model when the propagation and interaction for wave problem is considered. According to Valliappan, *et al.* (1984), the maximum element size should not be larger than the critical length (as defined by Eq. 4.3.1.1) governed by the shortest wavelength that propagates within the medium.

$$d \leq \varsigma \lambda$$ (4.3.1.1)

Where $d$ is the largest element size, $\varsigma$ is a threshold constant of 0.2, $\lambda$ is the shortest wavelength of interest.

The excitation force used was a short, sharp, cosine-shaped pulse with a duration of 0.1ms. The Rayleigh wave speed in the top layer of the pavement is around 1400m/s according to the pavement model profile (Table 4-2). Thus, the largest element size (Eq 4.3.1.1) was 0.028m here. Considering large element dimensions act as a low-pass filter and the computing ability of the workstation used, $d$ was set as 0.015m for areas of interest. A gradually coarser meshing strategy was used for the outer compensation and absorbing
layer to reduce the total element number and computational time required (Fig 4-6). Since
the simulation is interested on the transient response in time domain, commercially built-
in outer layers as PML (Perfectly Matched Layer) in frequency domain analysis could not
be applied. This compensation and absorbing layer would supply the displacement freedom
on the boundary of the inner fine meshing area to ensure the property as infinite layered
half space. The damping ratio was set as a continuously increasing as function of the
distance from the boundary of inner fine meshing area. The minimum value is the same as
the damping ratio on the inner boundary and grows exponentially to form an absorbing
outer layer without reflection from the outer boundary – as described by Eq. 4.3.1.2.

\[ \eta_s(r)_{r \geq r_0} = \eta_{s0} e^{\alpha(r-r_0)} \]  

(4.3.1.2)

where \( \eta_s(r) \) is the loss factor as damping ratio at position \( r \) from the source, \( \eta_{s0} \) is the
loss factor of the inner area, \( r_0 \) is the length of the inner area, and \( \alpha \) is a coefficient to
control the exponential growth. The geometric relationship is presented in Fig. 4-7.

Table 4-2 Asphalt concrete highway pavement profile parameters

<table>
<thead>
<tr>
<th>Asphalt Concrete Pavement Parameters</th>
<th>Thickness(m)</th>
<th>Poisson’s Ratio(( \nu ))</th>
<th>Modulus of Elasticity, E (MPa)</th>
<th>Unit weight (kg/m³)</th>
<th>Loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Concrete</td>
<td>0.127</td>
<td>0.4</td>
<td>13790</td>
<td>2242.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Base</td>
<td>0.1524</td>
<td>0.45</td>
<td>6895</td>
<td>1842.13</td>
<td>0.06</td>
</tr>
<tr>
<td>Sub-Base</td>
<td>0.4572</td>
<td>0.45</td>
<td>551.6</td>
<td>1762</td>
<td>0.11</td>
</tr>
<tr>
<td>Sub-Grade</td>
<td>( \infty )</td>
<td>0.45</td>
<td>206.85</td>
<td>1762</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Figure 4-6 Meshed geometry with varying element sizes and absorbing layer

Figure 4-7 Diagram of setting the loss factor for the absorbing layer

(3) Boundary condition constraints
To simulate the transient wave propagation problem in half infinite spaces and infinite plates, compensation and absorbing layers surrounded the interested core domains’ outer boundary conditions (BCs) to release the constraint of the displacement and realize non-reflection from the edges (Ke, *et al.*, 2009). The improvement in this model was the concept of vibration displacement release for the interested core domains’ edges to get close to the half infinite space effect.

The other critical BC is the coupling interface between the air-fluid and the pavement-structure. The fluid pressure caused a fluid load on the solid structure while the structural acceleration affected the fluid domain as a normal acceleration (COMSOL Multiphysics 3.5a, 2009). Eqs. 4.3.1.3–4.3.1.5 summarized this coupling.

\[
F_r = p n_{r_{-acp}} \quad (4.3.1.3)
\]

\[
F_z = p n_{z_{-acp}} \quad (4.3.1.4)
\]

\[
a_n = a_r n_r + a_z n_z \quad (4.3.1.5)
\]

Where \( F_r \) and \( F_z \) are the radial and vertical fluid loads on the solid boundary, \( n_{r_{-acp}} \) and \( n_{z_{-acp}} \) are the corresponding unit vectors and \( p \) is the acoustic pressure. \( a_n \) is the normal acceleration affecting the fluid domain. \( n_r \) and \( n_z \) are the radial and vertical unit vectors while \( a_r \) and \( a_z \) are the corresponding accelerations, respectively.

(4) Model material properties and de-bonding description
The parameters used to describe the stratified half space by regular highway asphalt pavement structural properties in United States as Table 4-2.

The attenuation incorporated in model were the loss factor parameters. Two types of de-bonding are introduced, with impact source locations (Fig 4-8), giving a total of four cases.

Figure 4-8 De-bonding Cases A, B, C and D

Case A and B were the open de-bonding happened at the interface of top layer and lower 2nd layer. A 1mm thick, 0.5m in radius thin plate cavity was embedded just under the impact point (black arrow) in Case A with the same thickness, 1m in length thin plate cavity 0.8m
from the left edge of the cavity to the impact point. Similarly, Case C and D were the closed
de-bonding. Case C had the same geometry and location with Case A while Case D was
the same with Case B except that the cavity was replaced by poor shear modulus material
which shared the same other parameters with the local materials. For Case A and B, isotropic elastic material model was employed; for Case C and D, viscoelastic material
model was used.

The bulk modulus and shear modulus for Cases C and D could be derived as

\begin{align*}
K &= \frac{E}{3(1-2\nu)} \\
G &= \frac{E}{2(1+\nu)}
\end{align*}

Where \( K \) is the bulk modulus, \( G \) is the shear modulus, \( E \) is Young’s modulus, and \( \nu \)
is Poisson’s ratio.

To simulate a poor shear interact closed de-bonding, the shear modulus was reduced to one
tenth as its normal value.

(5) The impact-response simulation

An easy way to study the dynamic characteristics of the pavement structure was to input a
unit impact excitation function (Dirac delta function). Then, the response signals would be
the transfer function of the dynamic system. Other types of response could be the
convolution of the response to the unit impact. The model applied a quite sharp and short
single cosine shape pulse \( F_I \) whose integral area is set to one to approximate the Dirac delta
function (Eq. 4.3.1.8).
Where \( T = 0.1\text{ms} \). The negative sign indicates the positive vertical z axis pointed upward. Due to this excitation frequency, the excited Rayleigh wave had a cut-off frequency of 10kHz.

(6) Verification of the model

The finite element model was verified through analysis of the intuitive wave shapes and through comparison to analytic critical values of wave features.

A direct validation method was air-coupled radiating Rayleigh wave shape from the snapshot of the simulation results. From the snapshot (Fig. 4-9), two main wavefronts could be identified easily as the radiating (leaky) Rayleigh wave and the direct impact acoustic wave. The first was a plane wave with a Rayleigh angle decided by the ratio of wave speed in air and solid, the latter was a spherical wave generated by the impact monopole source. The Rayleigh angle gained from the simulation result was 15.25 degrees comparing with the theoretical value of 14.34 degrees. The difference could be caused by the sub-layers effect to the top thin layer when the theoretical solution was calculated by the top layer parameter as uniform infinite half space. Such a kind of radiating Rayleigh wave shape could be a validation of the effective coupling of the air (fluid) and the solid (structure) multiple physics. Similar validation was given by Zhu, et al. (2008).

\[
F_t = \begin{cases} 
-20000\sin(\pi100000(t+0.5T))^2 & (for \ -0.5T \leq t \leq 0.5T) \\
0 & (for \ t < -0.5T \ or \ t > 0.5T) 
\end{cases} \quad (4.3.1.8)
\]
Figure 4-9 The acoustic pressure wave shape snapshot after 0.8ms by impact for healthy pavement

On the other hand, the simulation results could be verified by analytical solution of the wave speed of Rayleigh wave in homogeneous infinite half space (Zhu, et al., 2009). Since the speed of surface wave is mainly decided by the top layer parameter for pavement-like structure, the analytical solution by the top layer parameter would be close to the stratified 4-layer model result. According to the parameters of the pavement used in Table 4-2, the Rayleigh wave speed theoretically would be 1396.07m/s (take top layer as homogeneous infinite half space, by Eqs. 3.1.2 and 3.1.4) when the speed calculated from FEM model was 1382 m/s (4-layer half space). Besides, the extracted simulated data was employed for dispersion curve measurement study in later chapters. The results by the simulated data coincided with the theoretical expectation very well.

(7) Results and discussion
The finite element model was unique to offer the opportunity to give insight into any point in the whole field of interest. Also, defects with complicated geometry could be studied. It could be used to find the optimal excitation and receiver styles and installation positions in future research. In addition, it helped to extract data for post-processing with high flexibility. In this work, the locations of the receivers were set at 9 different points along the air-pavement interface line. The data of interest included first principal stress in elastic solid, the vibration displacement and the total acoustic pressures at the interface surface and 0.2m high above the interface surface.

In order to compare and analyze the different de-bonding cases, the excitation source, geometry and model parameters, and boundary conditions were all restricted to maintain the same for four de-bonding cases (Fig 4-8) together with healthy case as reference. One finding from the simulation results was the intuitive wave shapes in propagation, which make the abstract process visible.

Fig. 4-10 shows the comparison of the elastic stress wave in pavement solids of three cases (Fig. 4-8) at 0.125ms after the impact. The multiple-layered healthy pavement model had a helical curve shape due to the refraction and reflection at layer interface as (a). However, the open de-bonding as (b) had a ‘V’ shape wavefront because of reflection from the de-bonding thin cavity. The closed de-bonding (c) exhibited wavefront shape very similar to healthy pavement in (a). Meanwhile, the stress intensity distributions were almost the same for (a) and (c) for both the shapes and the maximum values. In contrast, (b) owned a relatively strong stress intensity as high as 242.5Pa. In this case, the open de-bonding had a strong dynamic difference when compared to the other cases. For the close de-bonding, which still had material to fill the de-bonding, but had a poor shear connection, was hard
to tell the difference. Other interesting phenomena were the initial separations of the P-wave from the S-wave and the Rayleigh wave concentrates at the top surface.

1ms after the impact, the Rayleigh wavefronts arrived at the de-bonding zone for Case B and D. The comparison of Case B, D and healthy pavement model was given as Fig 4-11.

Figure 4-10 The snapshot of the elastic solid waves in pavement at 0.125ms after the impact; (a) healthy; (b) Case A; (c) Case C

Fig. 4-11 illustrates the Rayleigh wave passing through and interacting with the de-bonding. Between the four cases, the most difference was again for the open de-bonding in Case B (b). One more Rayleigh surface wave, which grew downward and propagated along the open de-bonding interface, could be identified as (b). Meanwhile, the energy distributed during reflections was more apparent, in contrast to (a) and (b). And the sort of the solid stress was: Case B (32.2Pa)> healthy (28.8Pa)> Case D (26.7Pa). Due to the more freedoms release, the vibration caused stress became larger. The poor shear contacting closed de-bonding fell as the smallest. One explanation might be the weak shear modulus allowed
the P-wave passing through the interface easier, so, more energy went to the P-wave intensity make both S-wave and Rayleigh wave intensity less slightly. Besides, Fig. 4-11 shows Case D was quite closed to healthy pavement. In this case, to detect the closed de-bonding with weakened material properties might be harder by Rayleigh wave.

Figure 4-11 Snapshot of elastic stress wave in pavement at 1 ms after impact; (a) healthy; (b) Case B; (c) Case D

Besides the intuitive wave shape, the simulated signals, more significantly, could test the de-bonding through a non-contact and non-destructive, manner through the acoustic radiating surface (Rayleigh) wave – which occupies the main energy of the elastic waves and contains characteristic information of the pavement materials. The acoustic pressures at the pavement surface 0.75 m horizontally away from the impact point were extracted from the post-processing. As shown in Fig 4-12(a), for the impact load directly above the open de-bonding (Case A), the acoustic pressure was almost twice as large as for the healthy pavement. The acoustic pressures of Case C fell to the lowest and the other cases (Case B, D, and healthy) looked very similar to each other, as shown in (b). In addition, The P-wave, radiating surface (Rayleigh) wave and direct sound wave (mechanical impact monopole) could also be identified from Fig. 4-12, respectively.
To test the feasibility of using an air-coupled acoustic sensor, such as microphone, which picks up the sound signal at some height above the pavement surface, a comparison between the acoustic pressure at 0.2m above the surface and directly on the surface from the same horizontal source-receiver distance was given as Fig. 4-13.

Similar wave shapes but with a slight amplitude decay and a significant time delay were found in Fig. 4-13. For the open de-bonding Case A, sound pressure level in dB reference
as 1m, 20 µPa at 0.2m height was still 42 dB for peak value, only 2 dB lower than the surface counterpart which was 44 dB. This demonstrates the encouraging prediction which showed the opportunity to detect the de-bonding hidden under the pavement top layer through an air-coupled sensor such as a microphone.

Additional interesting characteristics of open de-bonding were found by frequency spectrum analysis, as shown in Fig. 4-14. The air pressure of open de-bonding structure subjecting to an above centered impact load (Case A) had obvious large peaks around 200 Hz and 1400 Hz, respectively. One peak value of 1.1 at 200 Hz was about 7.3 times as large as the 0.15 of healthy pavement. Another peak value of 0.7 at 1400 Hz was about 7 times as large as the 0.1 of healthy layers. At the other, higher frequency range, the air pressure of open de-bonding structure was 50% larger. This result reinforced a hope to detect the subsurface open de-bonding by the radiating surface (Rayleigh) wave when there was an excitation source applied above the de-bonding zone.

![Image](image.png)

Figure 4-14 Frequency spectrum comparison; (a) healthy; (b) open-delamination

(8) Summaries of FEM
A finite element model of a regular highway pavement, with large scale size and high mesh resolution, was created with the help of a ThinkStation D20 workstation. The challenge was the transient response computing time due to the large computational effort with 215,000 elements of interest. In order to solve the dynamic response of a complicated, debonding embedded, stratified pavement structure, the finite element model is a valid alternative solution when there is neither a closed-form analytical solution nor an existing pavement test bed whose material parameters are known. The model is verified by the coupling wave shape and critical parameters from a semi-analytical solution. The effective coupling of the air-fluid and pavement-structure makes the acoustic signals above the pavement surface provide information from radiating surface (Rayleigh) wave to detect subsurface de-bonding. The specific findings are summarized as follows.

1. Air coupled radiating surface (Rayleigh) wave could be identified even as high as 0.2m above the pavement surface.

2. The surface (Rayleigh) wave on the pavement surface and the corresponding radiated acoustic wave take main part of the energy from the pavement structure vibration.

3. The comparison of acoustic signals from the two main types de-bonding with healthy pavement demonstrates the opportunities to detect the defects hidden subsurface by non-contact and NDT acoustic signals method.

4. Resonant frequencies of de-bonded top layer could be identified through the acoustic pressure in air measured 0.25m outside the de-bonding area edge. This provides a chance to diagnose subsurface defects in pavement remotely (Case A).
4.3.2 Numerical Simulation of Acoustic Radiating Surface Wave

FEA is a good tool to understand the physical foundation and study feasibility when the complicated geometry is involved. The subsurface defect(s) geometry could be embedded easily in a FEA model, as in the previous section, but hard for numerical simulation by programming. However, due to the simulation objectives, it is not efficient for FEA to study the optimal operation for variant scenarios. In order to study the pavement vibration response and the acoustic radiating of surface waves efficiently, a numerical model has been created as a compensation.

This numerical model is an expansion of numerical simulation for the surface wave method with adding air-coupling for acoustic radiating surface waves. Based on the numerical modeling of surface wave experiment, the model simulates the radiated acoustic wave from the pavement surface by using particle acoustic radiation principles.

(1) Elastodynamics of layered half space simulation

Driven by the research of the surface wave based methods for ground NDT, numerical forward modeling is demanded as a basic analysis tool for both optimal prediction and inversion iteration reference. The numerical methods to model a layered half space mainly consist of stiffness matrix method by Kausel et al. (1981), discrete layer stiffness matrix by Waas et al. (1972), thin layer method by Lysmer et al. (1972), and elastodynamic finite integration technique (EFIT) by Fellinger et al. (1995).

The stiffness matrix method has been widely adopted by soil mechanics community. Developed from the Haskell-Thomson transfer matrix (Thomson, 1950; Haskell, 1953), this method has the benefits of symmetric matrix, arbitrarily layered soils, cylindrically
symmetric loading, and so on. Therefore, the stiffness matrix method is suitable to solve not only fundamental modes, but also multi-mode involved wave propagation. For surface wave propagation and its vibration response study, the stiffness matrix method is fairly popular and also be selected as a numerical modeling tool for the author's research. The specific details would be discussed in the subsequent section.

Discrete layer stiffness matrix is somewhat a FEA method but with a viscous absorber outer boundary to avoid the reflections with known incident angle of P-waves and S-waves. It was a substantial improvement for early FEA method to solve the infinite boundary wave propagation applications. For a homogenous half space, the incident angle of waves is easy to predict and describe. However, when the problem extends as layered half space, it becomes difficult to predict the incident angle of waves due to the complicated reflection and refraction. It is a limitation for this method.

Thin layer method is an approximate alternate to direct stiffness method. It uses polynomial shape functions to represent the vertical variation of displacement and tractions. It reduces the numerical calculation burden with only polynomial functions instead of transcendental functions for the stiffness matrices. The trade-off of the simplification is the limitation that only free-free boundary conditions for layers or supported by a rigid stratum. In order to simulate the layered half space, the combination with half space element is required.

The elastodynamic finite integration technique (EFIT) applies velocity-stress formalism on a staggered spatial and temporal grid complex. EFIT is a time-space simulation scheme and the integration starts from linear equations of the Cauchy equation of motion and the deformation rate equation. The integration is realized over the control volume and the
boundary surfaces. The benefits include robustness to the variant boundary conditions and stable computing and prediction of the wavefronts.

(2) Stiffness matrix method

Due to the advantages and successful applications in surface (Rayleigh) wave NDT as mentioned above, the stiffness matrix method was utilized for numerical simulation. Although the stiffness matrix method is powerful to supply the numerical solutions for flexible excitation sources (transversal impact, line source, exploration within half space, and so on), the specific application concerns the response from a uniform vertical circular loading. It is a reasonable description for an impact source for surface wave method, and later for approximating tire loading.

The response of the loading is cylindrically symmetric, so it is natural to use cylindrical coordinates, as shown in Fig. 4-15.

Figure 4-15 Circular impact force on layered half space
In Fig. 4-15, $P_0$ is the intensity of the uniform loading and $R_0$ is the radius of the circular loading. To simplify the expression of the stiffness matrix method, the description of the procedure would be formed in the frequency-wave number (f-k) domain. Therefore, the loading by Hankel's transform in the f-k domain would be as Eq. 4.3.2.1.

$$q(k) = -\frac{P_0 R_0}{k} J_1(kR_0)$$

(4.3.2.1)

where $J_1$ is the 1st kind Bessel function of 1st order.

The global governing equation of stiffness matrix is as Eq. 4.3.2.2.

$$[K][U] = [Q]$$

(4.3.2.2)

where $[K]$ is the global stiffness matrix assembled by layers with finite thickness and half space, $[U]$ is the global displacements of corresponding degrees of freedom and $[Q]$ is the global forces of interfaces relating to the displacement degrees. Since the Shear Horizontal (SH) and Shear Vertical (SV)-P waves are decoupled in this method, globally, they could be separated as Eq. 4.3.2.3 and 4.3.2.4.

$$[K]_S [U]_S = [Q]_S$$

(4.3.2.3)

$$[K]_V [U]_V = [Q]_V$$

(4.3.2.4)

Usually, only the vertical component is of interest for surface wave method, so Eq. 4.3.2.4 is used for following procedure.

The material damping is incorporated by complex moduli of the layers. The imaginary part would be the material attenuation.
The essential components needed for stiffness matrix element are summarized as follows:

\[ p = \sqrt{1 - \left(\frac{\omega}{k\alpha}\right)^2} \]  
\[ s = \sqrt{1 - \left(\frac{\omega}{k\beta}\right)^2} \]  
\[ \alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}} \]  
\[ \beta = \sqrt{\frac{\mu}{\rho}} \]

where, \( \lambda \) is the Lame's 1st constant, \( \mu \) is Lame's 2nd constant, which owns physical meaning as shear modulus.

For the SVP waves, when \( k > 0, \omega > 0 \):

\[ C_p = \cosh(kph) \]  
\[ S_p = \sinh(kph) \]  
\[ C_s = \cosh(ksh) \]  
\[ S_s = \sinh(ksh) \]

where \( h \) is the thickness of layers. For layers with finite thickness:

\[ D = 2(1 - C_p C_s) + \left(\frac{1}{ps} + ps\right)S_p S_s \]
For an infinite half space:

\[
\Delta = ps - \left( \frac{1 + S^2}{2} \right)^2
\]  
(4.3.2.14)

\[
K_{11} = 2k\mu \begin{bmatrix}
\frac{1 - s^2}{2D} & \frac{s}{2} \left( C_p C_S - ps C_S C_p \right) & \frac{1 - C_p C_S + ps S_p S_S}{p} \\
\frac{1 - C_p C_S + ps S_p S_S}{p} & \frac{s}{2} \left( C_p C_S - ps S_p S_S \right) & \frac{1 - s^2}{2} \left( C_S S_p - ps C_p S_S \right) \\
\frac{1 - s^2}{2} \left( C_S S_p - ps C_p S_S \right) & \frac{1 - s^2}{2} \left( C_S S_p - ps C_p S_S \right) & \frac{1 + s^2}{2} \begin{bmatrix} 0 & 1 \ 1 & 0 \end{bmatrix}
\end{bmatrix}
\]  
(4.3.2.15)

\[
K_{22} = 2k\mu \begin{bmatrix}
\frac{1 - s^2}{2D} & \frac{s}{2} \left( C_p C_S - ps C_S C_p \right) & \frac{C_p C_S - ps S_p S_S - 1}{p} \\
\frac{C_p C_S - ps S_p S_S - 1}{p} & \frac{s}{2} \left( C_p C_S - ps S_p S_S \right) & \frac{s}{2} \left( C_p C_S - ps S_p S_S \right) \\
\frac{s}{2} \left( C_S S_p - ps C_p S_S \right) & \frac{s}{2} \left( C_S S_p - ps C_p S_S \right) & \frac{1 + s^2}{2} \begin{bmatrix} 0 & -1 \ -1 & 0 \end{bmatrix}
\end{bmatrix}
\]  
(4.3.2.16)

\[
K_{12} = 2k\mu \begin{bmatrix}
\frac{1 - s^2}{2D} & \frac{s}{2} \left( ps S_p - S_S \right) & \frac{C_p - C_S}{p} \\
\frac{C_p - C_S}{p} & \frac{s}{2} \left( C_S - C_p \right) & \frac{1}{p} \left( ps S_p - S_p \right)
\end{bmatrix}
\]  
(4.3.2.17)

\[
K_{21} = K_{12}^T
\]  
(4.3.2.18)

For each layer with finite thickness, there are four elements as \(K_{11}, K_{12}, K_{21}, \text{ and } K_{22}\) for its sub-matrix. For the infinite half space, there is one element as \(K_{\text{half-space}}\) for its sub-matrix.

After all these elements are prepared, the global stiffness matrix could be assembled, for example, three layers plus half space as Eq. 4.3.2.20.
It could be found that the coupling between adjacent layers is implemented by adding of sub-matrix $K_{ii}$ on the diagonal, where the superscript number denotes the layer. The efficiency of computing with stiffness matrix is ensured by the triple diagonal matrix with zero elements.

For the displacement vector, correspondingly, each layer's SVP sub-vector takes the form of Eq. 4.3.2.21.

$$u_{SVP} = \begin{pmatrix} u_r \\ u_z \end{pmatrix} \quad (4.3.2.21)$$

For the force vector, each layer's SVP sub-vector would be zeros for all elements except the loading degree of freedom as vertical on top layer surface, which is in the form of Eq. 4.3.2.22.

$$q_{SVP} = \begin{pmatrix} 0 \\ q(k) \end{pmatrix} \quad (4.3.2.22)$$

where $q(k)$ is as Eq. 4.3.2.1.

Then, the displacement response for all degrees of freedom, globally, would be as Eq. 4.3.2.23.
Not all the displacement response would be of interest; for the surface wave measurement, only the vertical displacement on the surface of top layer is applied for simulation. It is \( u_z^{(1)} \) as in above equation. To simplify, the desired response could be express alternatively as Eq. 4.3.2.24.

\[
\begin{align*}
\begin{pmatrix}
  u_r^{(1)} \\
  u_z^{(1)} \\
  \vdots \\
  u_z^{(\text{half-space})}
\end{pmatrix} &= \left[ K \right]^{-1}_{SVP}
\begin{pmatrix}
  0 \\
  q(k) \\
  \vdots \\
  0
\end{pmatrix}
\end{align*}
\] (4.3.2.23)

Until this state, the displacement response \( u_z^{(1)} \) is obtained, but within the f-k domain. For analysis in the time-space (t-r) domain, it needs the inverse Hankel transform to convert from the wave number domain into space domain in the radial direction and inverse Fourier transform to convert from the frequency domain into the time domain. The first step is realized by Eq. 4.3.2.25.

\[
\begin{align*}
  u_z^{(1)} &= \left[ K \right]^{-1}_{SVP} (2, 2) \times q(k)
\end{align*}
\] (4.3.2.24)

where \( J_0 \) is 1st type Bessel function of 0 order; \( J_1 \) is the 1st type Bessel function of 1st order. This Hankel inversed \( u_z^{(1)}(r) \) is a complex number with respect to each frequency.

The complex format originates from the complex \( u_z^{(1)}(k) \).
Combine the $u_{z0}(r)$ in the whole frequency range in the study scope, and through inverse Fourier transform, it would achieve the time history record along the radial distance from the source.

Following this procedure, a numerical simulation of typical flexible pavement, as in Table 4-3, was created. Whose profile as shear velocity is presented by Fig. 4-16.

Table 4-3 4-layer pavement model profile

<table>
<thead>
<tr>
<th>Layer</th>
<th>$S_v$ (m/s)</th>
<th>Density (kg/m$^3$)</th>
<th>Poisson ratio ($v$)</th>
<th>Damping ratio</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>1500</td>
<td>2400</td>
<td>0.3</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1200</td>
<td>2400</td>
<td>0.3</td>
<td>0.02</td>
<td>0.15</td>
</tr>
<tr>
<td>Layer 3</td>
<td>300</td>
<td>1900</td>
<td>0.35</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>Half space</td>
<td>200</td>
<td>1900</td>
<td>0.35</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-16 Pavement profile as shear velocity

In order to study the theoretical dispersion curve, the dominant surface wave mode is identified by searching for the maximum value of vertical surface displacement $u_z^{(1)}(k)$ in the wave number domain at each frequency of interest. The specific idea was first
proposed by Zomorodian et al. (2006). The phase velocity and wavelength are related to frequency and wave number as Eq. 4.3.2.26 and 4.3.2.27. In the case of pavement model, as in Table 4-3, the predominant dispersion curve as phase velocity versus wavelength is shown in Fig. 4-17.

\[ \lambda = \frac{2\pi}{k} \]  

(4.3.2.26)

\[ V_c = \lambda f = \frac{2\pi f}{k} \]  

(4.3.2.27)

Figure 4-17 Dispersion curve of the 4-layer pavement model

A typical displacement response at 150Hz frequency is demonstrated with Fig. 4-18 to show both the real and imaginary portions along the distance from the source. The circular loading is with 100Pa intensity and 5cm radius. It could be found the imaginary part has \( \pi/2 \) phase difference with real part and the former decays faster. Similar results from
Gucunski et al. (1992) was also given by using the same pavement profile, it verifies the accuracy of the created model and the numerical program.

Figure 4-18 Displacement response along the radial distance from source

The whole wave field could be further described with a space-frequency (r-f) contour as Fig. 4-19 by the same pavement profile and loading.

Figure 4-19 Real part of displacement r-f contour
It could be found in Fig. 4-19 that the ridges in the contour are nearly continuous with decreasing frequency with respect to distance. This can be explained that wave components with longer wavelengths propagate more easily further, while the short wavelength components are centralized to within the near-source field. The imaginary part of displacement could also be visualized in a similar way. Knowing both the real and imaginary portions of displacement in the whole wave field, it is ready to study the optimization of the impact source style and the receiver arrangement numerically.

(3) Acoustic radiating above the ground surface

In order to fulfill the objective of non-contact acoustic sensing, an expansion to study the acoustic radiating from the surface vibration was realized based on the built-up numerical pavement model from the previous section.

The acoustic-structural multi-physics coupling was achieved by FE model previously mentioned; however, it would not be efficient to study the optimal testing configuration through FEA for variant typical scenarios of ground truth. The numerical acoustic radiating model was expanded for higher efficiency. The coupling of solid ground domain and acoustic air domain is mutual. The vibration acceleration on the ground surface excites acoustic particles' vibration. Inversely, the load force from sound wave also impacts the ground surface. However, the latter effects could be ignored due to the extreme contrast of stiffness between air and asphalt /concrete material. To simplify the model, only the acoustic radiating from the ground surface is considered.

(3.1) Study of acoustic radiation for time harmonic excitation
With given velocity of a vibrating plane, Rayleigh’s second integral will calculate its acoustic radiating by integrating the velocity in the frequency domain over the whole plane surface (Fig. 4-20) for time harmonic vibration. Rayleigh’s second integral was once difficult to implement numerically, after the work by Williams et al. (1982), the numerical evaluation has become convenient.

![Figure 4-20 Planar radiator diagram](image)

The fundamental expression of this integral is as Eq. 4.3.2.28, the $dx’, dy’$ form the surface element to integrate over. $R$ is the distance from the radiator to the receiver point.

\[
p(x, y, z) = -i\omega \rho \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} v(x’, y’) \frac{e^{ikR}}{2\pi R} dx’dy’
\]  

(4.3.2.28)

where $\omega$ is the angular frequency of interest and $\rho$ is the density of the fluid in acoustic domain. $v(x’, y’)$ is the local normal velocity of the planar radiator. By introducing the Green’s function ($G$), and a kernel $h$, as follows, Eq. 4.3.2.28 could be express as a convolution as Eq. 4.3.2.31.

\[
h(x, y, d) = -i\omega \rho G(x, y, d)
\]  

(4.3.2.29)
with Green’s function as Eq. 4.3.2.30 and \( d \) is height from the plane.

\[
G(x, y, d) = \frac{1}{2\pi} \frac{\exp(i k \sqrt{x^2 + y^2 + d^2})}{\sqrt{x^2 + y^2 + d^2}} \quad (4.3.2.30)
\]

\[
p(x, y, d) = v(x, y) \circ h(x, y, d) \quad (4.3.2.31)
\]

In this wave, it is easy to realize this convolution in frequency domain and then inverse by IFFT as Eq. 4.3.2.32.

\[
p(x, y, d) = F^{-1} [\hat{V}(k_x, k_y) \circ \hat{H}(k_x, k_y, d)] \quad (4.3.2.32)
\]

One more bridge to realize the integration is to transform the calculation from Cartesian coordinates to cylindrical coordinates since the displacement response has been determined in the latter.

\[
p(R, \theta, \phi) = -i \omega \rho \left( \frac{e^{ikR}}{2\pi R} \right) \hat{V}(k_x, k_y) \quad (4.3.2.33)
\]

with \( k_x = k \sin \theta \cos \phi \) and \( k_y = k \sin \theta \sin \phi \).

In frequency domain, the velocity response could be determined from displacement easily as just by a product of \( i \omega \). The vertical velocity response in the 4-layer pavement model is presented by Fig. 4-21.
With Rayleigh’s second integration, as mentioned above, and the calculated normal (vertical) velocity on the pavement surface, the time harmonic acoustic radiating above the surface could be achieved through the given procedure. Nonetheless, this procedure may not be proper for the transient impact study on the ground since current surface wave based methods usually use impulse excitation within a limited duration to study the transient response. To keep the comprehensive summary of air-coupled radiating, the procedure for time harmonic acoustic radiation is still discussed as above. For the transient impulse response study of acoustic radiation, a modified numerical model with reasonable simplifications will be introduced.

(3.2) Study of acoustic radiation for transient impulse response

In order to study the transient impulse response of the radiating surface (Rayleigh) waves, some simplifications are applied. Firstly, the acoustic pressure loading on the solid ground is still ignored due to the dramatic contrast of stiffness from air to pavement. Secondly, the
acoustic radiation of local ground surface particle vibration is assumed as the radiating surface wave source since the radiating surface wave is highly directional and propagates approximately as plane wave originating from corresponding ground surface particle. This consideration could be illustrated as Fig. 4-22.

As Fig. 4-22 shows, each local surface particle would radiate the corresponding radiating surface wave at its position. This surface wave radiation by particle vibration on the surface is highly directional. It could be considered that the radiating surface wave measured by microphone in Fig. 4-22 is radiated by the projection of the vertical vibration of the corresponding local surface particle on the radiating surface wave direction as $\xi \cos \theta$. Hereby, the minor contribution from horizontal vibration of the surface particle is negligible. Meanwhile, other particles on the surface wave propagation path would radiate their own radiating surface wave locally and form the plane wave above the ground. However, this kind of radiation from surface particle vibration is quite local so that only the indicated surface particle in Fig. 4-22 will contribute the radiating surface wave arriving at the microphone shown in Fig. 4-22. In this case, the radiating surface wave field above
the ground could be approximated with the combination of each local particle vibration radiation on the surface wave propagation path.

For each local surface particle taken as a point sound source, its acoustic pressure radiation on the surface as the radiating surface wave could be calculated through Eq. 4.3.2.34.

\[ p_0 = \rho c \omega \xi \cos \theta \] (4.3.2.34)

Where, \( \rho \) is the density of fluid as air, \( c \) is the sound speed in air, \( \omega \) is the angular frequency, \( \xi \) is the vertical displacement of the surface particle, and \( \theta \) is the Rayleigh angle respectively.

On the height of \( h \), the plane wave like radiating surface wave would attenuate by Stokes Law of sound attenuation as Eq. 4.3.2.35.

\[ p_h = p_0 e^{-\frac{\alpha h}{\cos \theta}} \] (4.3.2.35)

Where, \( p_h \) is the acoustic pressure of radiating surface wave on the height of \( h \), \( \alpha \) is the attenuation rate and defined as Eq. 4.3.2.26. It states that the amplitude of a plane wave decreases exponentially with distance traveled as \( h/cos\theta \), at a rate \( \alpha \).

\[ \alpha = \frac{2\eta \omega^2}{3\rho c^3} \] (4.3.2.36)

Where, \( \eta \) is the dynamic viscosity coefficient of the fluid (air, hereby, \( 1.81 \times 10^{-5} \) Pa at \( 17^\circ \mathrm{C} \)).

So finally, the radiating surface wave which modeled as plane wave at the height \( h \) radiated by local surface particle with the effective displacement \( \xi \cos \theta \) could be predicted as follows.
Eq. 4.3.2.37 indicates that the acoustic pressure of radiating surface wave depends on the fluid (air) material property such as density, sound speed, dynamic viscosity coefficient, and the known vertical displacement of ground surface particle as well as the specific frequency $\omega$ of interests. Recalling the ‘(2) Stiffness matrix method’ in above session, it is possible to calculate the surface displacement $\zeta$ of any distance $r$ from the impact source for a specific frequency $\omega$ similar to Fig. 4-18 showing. As for the Rayleigh angle $\theta$, it could be got as Eq. 4.3.2.38.

$$
\theta = \sin^{-1}\left(\frac{c}{c_R}\right)
$$

(4.3.2.38)

The $c$ is the sound speed in air and $c_R$ is the surface wave speed in ground, which could be approximated as the top layer surface wave speed when it is dominant.

Hereby, all needed parameters are given to predict the radiating surface wave field. Using the pavement profile as Table 4-3, which is the same profile used in Fig. 4 and Fig. 5 in Gucunski et al. (1992), the predicted radiating surface wave field (2cm above the ground) is presented in Fig. 4-23. The impulse applied on this profile has a contact radius of 5cm, 0.16kN peak magnitude and 0.1ms duration.
It could be learned the radiating surface wave would reach up to 62 dB and the strong fields happen around 2 kHz, 8 kHz, and 13 kHz, which attenuate slowly in the radial distance.

With the same profile and impulse, a FE model by COMSOL Multiphysics was also created to help aid in the verification of the numerical model for the radiating surface wave.

Fig. 4-24 and Fig. 4-25 indicate quite similar frequency spectrums predicted by FEA and numerical method at 0.2 m and 0.6 m away from the impulse source, respectively with the height of 2 cm. It could be found the magnitude of predicted acoustic wave field by numerical method is smaller than the prediction by FEA when the location is further from impulse. It could be explained for two main reasons.
Firstly, the FE model gives total acoustic pressure of all existing acoustic waves, which include other surface waves except Rayleigh waves, the direct sound wave due to the impulse contact and air-coupled radiation from P-wave and S-wave. In contrast, the prediction by numerical model is pure surface wave without other minor waves. That is also the reason for the minor differences of frequency spectrum at some frequencies. The
frequency spectrums by FEA have more zigzags, which seems noisier than the numerical method. The zigzags in frequency spectrum by FEA are the results of other acoustic waves beside the pure surface wave. The pure radiating surface wave makes the frequency spectrum by numerical method smoother.

Secondly, the FE model would overestimate the elastodynamic response of pavement due to the approximated treatment on the infinite half-space underneath the layers with finite thicknesses. Although an extension zone surrounding the high-resolution meshing zone was designed to simulate the infinite half-space in FE model, it might not be enough to achieve the effects of infinite half-space where the energy would enter with less reflection. In this case, a greater energy response would result, especially for larger distances from the impulse source because the quarter circle geometry is applied for the layered half-space. The response at farther locations would attenuate less due to the thinner layers to simulate the infinite half-space. In contrast, the numerical method solves the infinite half-space effects very well so that the elastodynamic response would be smaller comparing with FE model. This explains the results that the total acoustic pressure by FEA at 0.6m exceeds the numerical method at the 0.2m distance. Thus, the numerical model would supply more accurate prediction with larger, but reasonable attenuation along the propagation path. The similarity of the frequency spectrums of the acoustic wave between the FE model and numerical method verified the proposed simplification through local surface particle acoustic radiation and the Stokes Law of attenuation for plane wave. In fact, the latter has the advantages: a faster calculation; more accurate prediction of the attenuation along propagation path; larger simulation scale.
Furthermore, through IFFT, the time history signal of radiating surface wave could be predicted from the calculated frequency spectrum at a location of interest. Fig. 4-26 demonstrates the IFFT transfer results at 0.2m and 0.6m, respectively with the height of 2 cm above the ground, following the same wave field model as Fig. 4-24(b) and Fig. 4-25(b). Due to the limited discrete data points in the frequency domain, the transferred time history signal seems not smooth. However, it will not affect the value of the model in terms of prediction the response of impulse on pavement. Actually, the prediction in frequency domain is more important for the study.

![Figure 4-26 Predicted time history signal of radiating surface wave (2cm above the ground)](image)

### 4.4 Implementation of Radiating Surface Waves Sensing

#### 4.4.1 Sound Enclosure Design

Based on the understanding of the challenges of acoustic sensing for surface wave, an effort to de-noise the mechanical enclosure design has been tried and a field test validated its function.
The widely used air-coupled acoustic sensor could be a microphone. The measurement setting by microphone is diagrammed as Fig. 4-27.

![Microphone measurement setting up](image)

**Figure 4-27** Microphone measurement setting up

And the arrival time differences between the surface wave and direct sound wave would be as Eq. 4.4.1.1.

\[
\Delta t = \frac{\sqrt{r^2 + h^2}}{V_a} - \frac{r - h \tan(\theta)}{V_R} - \frac{h}{\cos(\theta)V_a} \quad (4.4.1.1)
\]

Using the material properties and the configuration settings of the microphone array, this arrival time difference could be estimated. For example, with \(r=0.5\)m and \(h=0.05\)m, this time lag can be 1ms, so it could be separated with correct sensing distance.

Fig. 4-28 shows an example of the surface wave measured by accelerometer (a) and the radiating surface wave measured by microphones (b). According to the comparison, it can be seen the first part of the microphone data arrives nearly at the same time and shows the similar feature as the accelerometer data. This part of data can be identified as the radiating surface wave. The second part of the microphone data is regarded as the direct sound wave.
from the hammer knocking because no signal is present in the acceleration signal counterpart at the same time.

Figure 4-28 Comparison of microphone signal with accelerometer signal. (a) Measured surface acceleration. (b) Measured acoustic above surface signal

In order to improve the signal to noise ratio (SNR) of acoustic data for the application for fieldwork, a sound barrier enclosure is designed to block the direct sound wave (impact noise) as well as the environmental noise. Fig. 4-29 shows the design and hardware realization. A steel cylinder is selected as the skeletal structure. A sound reflecting material with a more dense skin material wraps over the external surface of cylinder skeleton to reduce the penetration of outside noise. The acoustic noise would be mainly reflected on the more dense skin surface first when it touches the skin. Then the noise penetrating the
first reflection surface could be reflected by the steel cylinder wall again and attenuates in the form layer between the steel cylinder wall and the dense skin. A pyramid array pad is fitted in the internal surface of the skeleton and also the bottom circular surface to absorb reflections inside the chamber (Fig. 4-29(b)). The microphone is mounted in the center of the cylinder with 1 cm above the ringed end plane as red circle marked in Fig. 4-29(b).

Such a design would block the ambient noise and impact noise whose incident directions are almost perpendicular to the enclosure cylindrical surface. In contrast, the radiating surface wave from the ground vibration would easily reach the microphone.

Fig. 4-30 indicates the effect of this sound enclosure. The microphone is 0.2m away from the impact source. The comparison is realized with two impacts, one without enclosure and one with enclosure. Fig. 4-30(a) shows that without enclosure, the noise level is so high that the radiating surface wave can hardly be separated from the environmental noise in recorded data. After the enclosure is applied to the microphone (Fig. 4-30(b)), the radiating surface wave can be easily identified and extracted from the time history signal. Moreover, the enclosure blocks other ambient noise arriving before the radiating surface wave. As
could be observed in Fig. 4-30(b), the recorded acoustic signal before the radiating surface wave is satisfactorily close to zero. This indicates a high signal to noise ratio.

![Figure 4-30](image)

**Figure 4-30** Effects of the sound enclosure for microphone in noisy environment. (a) Without enclosure. (b) With enclosure

After the efforts, as noted earlier, to extract the radiating surface wave signal, the signal to noise ratio in the field work environment is studied using the Pingree Bridge Deck test. As Fig. 4-31(a) shows, the extracted radiating surface wave signal during impact is compared with the ambient noise during impact intervals. The average dB level for radiating surface wave is 96 dB, while the ambient noise contributes 75 dB. The signal to noise ratio is also indicated in Fig. 4-31(b) within 10 kHz. The SNR is around 20 dB, except at the very low frequency end. This could be caused by the low frequency vibration of the bridge structure. However, this low frequency data would not affect the profile analysis for shallow depths within 1 m, since the corresponding penetration depth with respect to wavelength is large.
4.4.2 Acoustic Signal Processing for Radiating Surface Wave

In addition to the hardware efforts to improve the SNR, a signal processing strategy with windowing and filtering are also used to extract the radiating surface wave for analysis. Since the MASS system is designed with the goal of being an autonomous signal processing prototype, a pre-processing program implementing the automatic windowing for the radiating surface wave is embedded in the software platform. The data acquisition is triggered by the impact acceleration through a professional shock accelerometer mounted coaxially on electromagnetic hammer core (Fig. 4-32). The accelerometer monitors the hammer impact and triggers the data acquisition as the starting point in the time history. The time stamp where the first apparent peak or valley (maximum absolute amplitude) appears in the recorded acoustic data is identified as the arrival time of the radiating surface wave. A time-window with a Hanning shape is applied to truncate the signal of the radiating surface wave. The window center is aligned with the time stamp of the radiating surface wave, while the window size is equal to the arrival time difference from the radiating
surface wave to the direct acoustic wave (Eq. 4.4.1.1). This windowing is realized automatically.

![Figure 4-32 Professional shock accelerometer on the hammer core](image)

Additionally, several criteria are used in the pre-processing program to ensure acquired signal quality, especially in a field work environment. Firstly, the impact quality itself is verified through its time historical shape as acceleration, and only sharp impacts with broadband excitation would be accepted. Secondly, the magnitude squared coherence between sensing channels are also verified within 100 Hz to 10,000 Hz (Eq. 4.4.2.1).

\[
|c_{xy}(f)| = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}
\]

(4.4.2.1)

Signals with low coherence in this range imply poor signal quality and would be neglected. Recorded signals that failed to pass the pre-processing criteria would be discarded for further processing. A message window would display to indicate more trials being needed. Only the acquired signals that satisfy the criteria are used as raw data for further processing.
The raw data with poor quality due to random environment noise such as low frequency ground vibrations would not be used for analysis.

This chapter summarized the feasibility, as well as the challenges of acoustic radiating surface wave sensing. FE and numerical models are established. The FEM supplied an intuitive visualization of the acoustic radiating surface wave, and characterized the debonded pavement from healthy pavement using acoustics. The numerical model was a further development for predicting the acoustic wave field with parametric study capability and with improved computational efficiency. Finally, acoustic sensing was implemented with both mechanical and numerical filters to access clean acoustic surface wave signals, which is prepared for the subsequent field test and dispersion curve analysis.
5 ITERATIVE WAVE NUMBER ESTIMATION FOR DISPERSION CURVE

5.1 Current Dispersion Measurement Methods and Difficulties

Dispersion curves could be measured with alternative methods as introduced in Chapter 3 (3.2 General principles and procedures of surface wave based methods). However, each method has drawbacks when used in certain applications or scenarios. Researchers have proposed modifications and criteria for post-processing corrections, however use of these corrections require a prohibitively complete understanding of the material, which limits practical implementation.

The SASW method is a revolutionary improvement upon the continuous surface wave (CSW) method. The improvement is realized by using broadband sharp impact testing to replace frequency-to-frequency testing by a fixed-frequency vibrator – which greatly improves efficiency. Nonetheless, SASW method has several drawbacks. The primary challenge is phase angle unwrapping. The phase difference between two receivers is required to determine phase velocity. The wrapped phase differences are bounded within interval of -\(\pi\) to \(\pi\), with frequency dependent phase discontinuities as shown in Fig. 5-1(a). To determine the real phase differences, the wrapped phase differences must be unwrapped by adding \(2\pi\) at the phase jumps to yield continuous phase differences, as shown in Fig. 5-1(b).
At early stages of SASW development, it was believed that phase difference wrapping occurred due to contaminated signals, which had a low coherence value between the two channels. However, Al-Hunaidi (1992; 1993) identified the real mechanism that leads to phase difference wrapping. It was found that even for high coherence frequency range, spurious angular cycles would be present and they would lead to a pseudo $2\pi$ folding. Through a forward numerical simulation of a 3-layered pavement model, it was determined that mode jumping caused the spurious angular cycles. Mode jumping is a special phenomenon where the layered half space has an irregular profile with stiff top layers (Rosenblad et al., 2008). The dominant mode would jump from an expected mode (eigenvalue of stiffness matrix) to another at a specific frequency. An example of this is shown in Fig. 5-2.
This mode jumping leads the irregular jumping of the accumulative angular cycle simultaneously, so the phase angle differences became wrapped. Based on this study, Al-Hunaidi concluded that phase angle is not a suitable analysis parameter in the SASW method. He also suggested to apply a larger source-near receiver space to allow the multiple dominant wave modes to converge with these spatial ranges. However, this recommendation was concluded from theoretical study, without considering the amplitude issue during field testing. If the test object is pavement structure, it requires a high resolution signal of short wavelength for the shallow depths of interest, so the large source-near receiver space is not practical for realistic implementation in the field.

One other main limitation of the SASW method is the multi-mode issue. When early SASW was applied in geophysical or seismologic sites, only the fundamental mode was considered for inversion. This limitation for geophysical or seismologic study is still acceptable since for these testing objects the profile is regular and the stiffness increases
with depth. For this kind of profile, the fundamental mode is dominant; as result, the mode jumping issues would not present. As more applications used to other layered ground such as pavement, unexpected results were obtained. Ali Zomorodian, et al. (2006) discussed this issue in the wave number domain. By comparing two typical profiles, as shown in Table 5-1, mode jumping among wave modes in the dispersion curve could be obtained clearly as shown in Fig. 5-3. It was observed that for regular profile, mode jumping was not present and the fundamental mode was dominant for the entire frequency range. However, for an irregular profile, mode jumping (from low to high modes) occurs.

Table 5-1 Two typical profiles (Ali Zomorodian, et al., 2006)

<table>
<thead>
<tr>
<th>Layer no.</th>
<th>Profile 1</th>
<th>Layer no.</th>
<th>Profile 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shear wave velocity (m/s)</td>
<td>Thickness (m)</td>
<td>Damping ratio</td>
</tr>
<tr>
<td>1</td>
<td>300</td>
<td>20</td>
<td>0.005</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>20</td>
<td>0.005</td>
</tr>
<tr>
<td>3</td>
<td>700</td>
<td>—</td>
<td>0.005</td>
</tr>
</tbody>
</table>
Figure 5-3 Dispersion curve of dominant mode: (a). Profile 1 in Table 5-1; (b). Profile 2 in Table 5-1. (Ali Zomorodian, et al., 2006)

With only two receivers, only the apparent (dominant) mode could be measured, but it would not be fundamental mode due to the irregular profile. This causes an incorrect inversion analysis if only the fundamental mode is considered.

For the MASW method, dispersion curve measurement understanding is improved because the information is expressed in 3D by a contour of dispersion curves instead of a single 2D curve. By multi-channel sensing, higher wave modes could be identified. However, the trade-offs are the need for many testing devices (receivers) and the complicated inversion process required to consider all the excited wave modes. For the f-k method, a similar trade-offs exist.
5.2 Iterative Wave Number Estimation Methods

The concept of wave number estimation by iterative fitting was introduced initially for evaluation of material damping in structures such as beams and plates by McDaniel et al. (2000a). This method uses spatially sparse response measurements, perhaps beyond the limitation of spatial Nyquist theory, and has been shown to be robust with respect to measurement with noise (McDaniel et al., 2000b).

The fundamental principle of the wave number estimation method is the reconstruction of the wave field by adjusting complex-valued wave numbers and corresponding amplitudes in an analytic representation of the wave field. The method fits experimental data from a vibrating damped beam successfully with a satisfactory accuracy to estimate the frequency-dependent damping. The imaginary part of the complex wave number is related to material damping. However, the fundamental principle of this method extends to any wave-bearing system and specifically accounts for multiple wave types.

This part of work extends the method to composite pavement structures, which are generally constructed by bonding homogeneous horizontal layers. Such structures support multiple wave types. The pavement may be modeled as a homogenous half-space when the differences among layers are small with respect to the aperture of interested depth underneath the surface. When the stiffness contrasts among layers are large, more generally, it is modeled as horizontally layered half-space.

(1). Description of the Method
The test configuration is assumed to be that of Fig. 5-4. At each frequency $\omega$, a local excitation generates waves in the pavement having axial displacements $u(r,t)$ normal to the surface given by

\[ u(r,t) = \text{Re}\{\tilde{u}(r)\exp(-i\omega t)}\]  \hspace{1cm} (5.2.1)

The spatial dependence is assumed to be a sum of waves

\[ \tilde{u}(r) = \sum_{n=1}^{N} c_n \exp(ik_n r) \] \hspace{1cm} (5.2.2)

where $c_n$ are the wave amplitudes and $k_n$ are the complex-valued wave numbers.

It is assumed that measurements have been made of the axial displacement at locations $r_m$ on the pavement surface for $m = 1, 2, ..., M$. The Fourier Transform is taken over time, such that at each frequency of interest, the complex amplitudes of the measured displacement values are denoted as $\tilde{u}_\omega(r_m)$. Requiring the analytical wave field to match the measured data yields

\[ A_m c_n = b_m \] \hspace{1cm} (5.2.3)
If the complex-valued wave numbers are known, this system may be solved for the wave amplitudes. If the number of measurement locations is equal to the number of waves, so that $M = N$, then $A_{mn}$ is square and the system may be solved for a unique set of wave amplitudes. If $M > N$, then the system is over-constrained and must be solved in a least-squares sense. If $M < N$, then the system is under-constrained and does not have a unique solution.

The method requires that $M > N$ and begins with estimates the complex wave numbers. These estimates are used in Eq. 5.2.3 and the equation is solved for the wave amplitudes. The wave amplitudes are substituted into the analytic wave field, Eq. 5.2.2, and the displacement values at the measurement locations are computed. A normalized mean square error, $\varepsilon$, between the analytic wave field and the measurements is computed according to

$$
\varepsilon = \sqrt{\frac{1}{M} \sum_{m=1}^{M} \left| \tilde{u} \varphi (r_m) - \tilde{u} (r_m) \right|^2} \sqrt{\frac{1}{M} \sum_{m=1}^{M} \left| \tilde{u} \varphi (r_m) \right|^2}
$$

(5.2.6)

The complex-valued wave numbers are then varied so as to minimize $\varepsilon$. The requirement that $M > N$ is essential. If $M = N$, then any choice of wave numbers would yield $\varepsilon = 0$. 

where

$$A_{mn} = \exp(ik_{m}r_{n})$$

(5.2.4)

$$b_{m} = \tilde{u} \varphi (r_{m})$$

(5.2.5)
Three implementation issues are important. Firstly, optimization algorithms may be used to expedite the progress. However, since most optimization algorithms require real-valued parameters, the real and imaginary parts of the wave numbers must be treated as independent real-valued parameters in the optimization. Secondly, if one does not have initial estimates of the wave numbers, then one can define their ranges and compute $\mathcal{E}$ over the ranges of all wave numbers. Then, the estimates of the wave numbers are taken to correspond to the global minimum in $\mathcal{E}$. Thirdly, one may use the optimized wave numbers at one frequency as starting guesses in the optimization of a nearby frequency. In this way, one may start at the highest frequency of interest and then step down in frequency.

(2). Complex Wave Number Search and Trace

The proposed method initializes its trace of the complex wave number at a start frequency point, which is often the maximum frequency under consideration. At that frequency, one evaluates the NMSE (Normalized Mean Square Error) over ranges of values for the real and imaginary parts of the wave number. It is indicated as a color contour. The complex wave number corresponding to a minimum in the NMSE 2-D plane is chosen as the estimate at that frequency. The successful search of the wave number at initial frequency point depends on the reasonable scan range for both real and imaginary part of wave number. The imaginary part is small compared to the real part. Eq. 5.2.7 and 5.2.8 indicate the scan range used in this work, where $s_1$ and $s_2$ are factors ranging from 1~2, 0.5~1, respectively. $f_0$ is the selected start frequency and a reasonable $c_p(f_0)$ needs to be guessed. Such kind of scan range pre-definition helps with shrinking the sweep calculation, meanwhile, better resolution in the physically reasonable range could be accessed.
After obtaining this estimate, the algorithm moves to the next lower frequency, using the estimate from the previous frequency as a starting point in an iterative search. Various optimization algorithms may be used for this step; the results presented here correspond to a downhill simplex method. The principal procedure of the proposed method is described in Fig. 5-5.

![Flow chart of the complex wave number estimation method](image)

**Figure 5-5** Flow chart of the complex wave number estimation method

(3). Robustness of the Method for Both Contact Sensing and Air-Coupled Non-Contact Sensing

The above method can be used not only for direct contact sensing, but also for air-couple non-contact sensing if a clean radiating surface wave could be extracted via microphone.

(4). Demonstrations of method and discussions

A large scale finite element model is established to provide synthetic signals of transient impact response of pavement. Both ground acceleration and acoustic radiation could be gathered. The model works as a forward numerical platform with prior knowledge of structure profile. The FEA model is realized with commercial software Comsol Multiphysics 3.5 by Lu, et al. (2010). A model of coupled fluid and solid half-spaces is
investigated first. The profile of the model is presented in Table 5-2 and the diagram of the simulated test is presented as Fig. 5-6(a).

**Table 5-2 Acoustic-Structural half space**

<table>
<thead>
<tr>
<th></th>
<th>elastic modulus $E$ [MPa]</th>
<th>density $\rho$ [kg/m$^3$]</th>
<th>Poisson’s ratio $\nu$</th>
<th>loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>7000</td>
<td>2000</td>
<td>0.4</td>
<td>0.06</td>
</tr>
<tr>
<td>Fluid (air)</td>
<td>n/a</td>
<td>1.22</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Hereby, the $r_1$, $r_2$, and $r_3$ are taken as 0.75m, 1.25m, and 1.75m, respectively. Note that the receivers are not required to have equal spacing with the present method.
(a). Contact sensing by acceleration (Case 1)

The simulated test using ground-pasted accelerometers is indicated in Fig. 5-6(a). The fluid half-space is air with density 1.22 kg/m³ and speed of sound as 343 m/s. Following much of literature, a frequency range of 50 Hz to 20 kHz is used. The trace of the complex wave number in the 2-D complex plane is indicated in Fig. 5-7 at two frequency points as example. The real part of wave number moves rightward in Fig. 5-7 from 1.54/m, then to 3.92/m as the frequency increases from 250 Hz to 650 Hz, for instance. Meanwhile, the imaginary part of the wave number remains roughly unchanged.

Figure 5-7 Contour of NMSE versus real and imaginary parts of wave numbers

The estimated wave number at the previous frequency could be used as initial estimate for adjacent frequency for next frequency. The iterative convergence would finally realize the trace of wave number in the entire frequency of interest. The real part of the complex wave
number is presented in Fig. 5-8(a). The curve in the figure displays a highly linear trend and the ratio of frequency over real part of wave number is proportional to the phase velocity, which indicates the phase velocity of the surface wave is constant with frequency. Fig. 5-8(b) shows the imaginary part of wave number, the smooth curve without apparent discontinuities or jump points conforms to the unitary mode of surface wave in a homogeneous elastic half-space. The negative value indicates decay with increasing radial coordinate, as expected. The NMSE for the iterative convergent procedure is shown in Fig. 5-8(c), where the low value which is below 0.04 confirms the confidence of the estimated wave number. Only three channels are used to get this result, which indicates the efficiency and robust of the proposed method in terms of the amount of sensing channels.

Figure 5-8 (a) Estimated real part of wave number for Case 1 (b) imaginary part of wave number (c) NMSE
For pavement NDT by stress wave, calculation of the dispersion curve is always a critical step. The theoretical prediction is described in Eq. 5.2.9, and 5.2.10, where $V_s$ and $V_{ph}$ are velocities of shear wave and Rayleigh wave, respectively.

$$V_s = \sqrt{\frac{E}{2\rho(1+\nu)}}$$ \hspace{1cm} (5.2.9)

$$V_{ph} \approx \frac{0.87 + 1.12\nu}{1 + \nu} V_s$$ \hspace{1cm} (5.2.10)

$$V_s \approx 1.1V_{ph}$$ \hspace{1cm} (5.2.11)

$$D = (0.3 \sim 0.5)\lambda$$ \hspace{1cm} (5.2.12)

According to the material parameters of the elastic half-space in Table 5-2, the theoretical phase velocity of the surface wave is 1052.50 m/s. The phase velocity of surface wave calculated by the proposed method adheres to the theoretical prediction closely in a broad band of frequency (Fig. 5-9(a)). The small difference in the higher frequency could be caused by the fluid-solid coupling effects on the surface wave. A contrast with traditional SASW method is presented in Fig. 5-9(b) presented by the real part of the wave number. The comparison shows the close agreement between the proposed method, the SASW, and the theoretical prediction. In addition, Fig. 5-9(b) indicates that the proposed method is accurate at lower frequencies where it matches the theoretical prediction perfectly. In contrast, SASW method only produces accurate results in a narrow frequency band from 8kHz to 12kHz. Moreover, the near-source receivers (ch1-ch2) give relatively poor dispersion estimates compared to the more distant receivers (ch2-ch3). It is due to
significant signal attenuation near the source being neglected. This demonstrates the advantage of sparse multi-channel simultaneous sensing (ch1, ch2, ch3) by the proposed method.

Figure 5-9 (a) Dispersion curve for Case 1 (b) real part of wave number

(b). Non-contact sensing by air-coupled sensor (Case 2)

A microphone array is placed 0.02m above the same locations of accelerometer array in the finite element model as Fig. 5-6(a). Similarly, Hanning window based filtering is applied to obtain acoustic radiation from the surface wave in the air while rejecting the direct acoustic wave from the impact. The estimated real part of the wave number is indicated in Fig. 5-10(b). A comparison between microphone sensing and accelerometer sensing is also shown in Fig. 5-10(b). The two curves overlap with each other in the whole band of frequency in interest, which validates the robustness of the proposed method for both contact sensing and non-contact air-coupled sensing. Based on the estimated real wave
number, an empirical inversion is processed to show the shear wave velocity varying with depth (Fig. 5-10(a)). The shear wave velocity in the shallow depth shows a linear trend as the shear wave velocity is around 1152m/s, compared to the theoretical value of 1118m/s. There is no sharp inflection in the curve which agrees with the homogeneous half-space model. The transition from acceleration sensing to acoustic pressure sensing maintains the profile characteristics as theoretical predication.

Figure 5-10 (a) Empirical inversion by acoustic pressure signal (b) real part of wave number comparison

(c). Stiff layer bonded on half-space with fluid-coupling (Case 3)

The fundamental feature of pavement profile could be presented as a substrate half-space bonded with a stiffer top layer, although more complicated layered paving on top of half-space could be extended further. To study the capability of the layer bonding depth
estimation, a finite element model is formed as Fig. 5-6(b) and Table 5-3. The positions of r1, r2, and r3 are kept the same with previous cases.

Table 5-3 Profile of fluid half-space coupled with layered solid half-space

<table>
<thead>
<tr>
<th></th>
<th>elastic modulus $E$ [MPa]</th>
<th>density $\rho$ [kg/m³]</th>
<th>Poisson’s ratio $\nu$</th>
<th>loss factor [1]</th>
<th>thickness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid half-space</td>
<td>n/a</td>
<td>1.22</td>
<td>n/a</td>
<td>n/a</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Solid top layer</td>
<td>7000</td>
<td>2000</td>
<td>0.4</td>
<td>0.06</td>
<td>0.5</td>
</tr>
<tr>
<td>Solid half-space</td>
<td>500</td>
<td>2000</td>
<td>0.4</td>
<td>0.06</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

The dispersion curve calculated by ground acceleration with the real part of wave number is presented in Fig. 5-11(a). The highly linear section above 2kHz of the dispersion curve corresponds to the stiff top layer, while the dramatic decreasing phase velocity in the lower frequency section corresponds to the soft, sub-grade, half-space. A comparison with SASW using the same synthetic signals is also presented as Fig. 5-11(a). The dispersion curve supplied by proposed method is closest to the theoretical dispersion curve from the Stiffness Matrix model, for the entire frequency range of interest. The dispersion curve given by receiver pair 1-3 with the SASW method overestimates phase velocity above 2kHz while the dispersion curves by receiver pairs 1-2 and 2-3 with SASW method underestimate phase velocity below 5kHz. The deviation of SASW results from the theoretical dispersion curve could be caused by the difficulty of phase angle unwrapping and the sensitivity to the spatial arrangement of the sensors. The inflection in empirical
inversion curve, as shown in Fig. 5-11(b), indicates the profile of the model. Shear velocity decreases around a depth of 0.5m. More complicated inversion procedures could be followed, however this work focuses on the wave number estimation procedure. Again, non-contact sensing is attempted with a microphone array placed at a height of 0.02m, as shown in Fig. 5-6(b). The inflection on the normalized ratio curve of imaginary over real part of wave number indicates the frequency matching with bonding depth as Fig. 5-12(a). Where the vertical line implies the theoretical calculation of the frequency is 650Hz corresponding to the designed bonding depth of 0.5m. The empirical inversion of shear velocity by acoustic pressure implies the bonding depth around 0.5m as Fig. 5-12(b). The results are similar with accelerometer array when microphone array is used instead. The robustness for non-contact sensing by acoustic radiation from surface wave is demonstrated.

![Figure 5-11 (a) Dispersion curve comparison (b) empirical inversion (acceleration)](image-url)
Defects could be hidden beneath the ground surface and can be indicated by changing stiffness due to the growth of de-bonding, voids, or outspread of small corrosion cores. To study the capability of proposed method for the subsurface defects, a FEA model is formed as Fig. 5-6(c) and the half-space materials are still as Table 5-2. For one scenario, the defect is modeled as a square with $s = 0.5\text{m}$ width and $a = 1\text{m}$ away from impact source while $d = 0.5\text{m}$ deep under the ground surface. The defect is characterized by its weak stiffness with $500\text{MPa}$ elastic modulus in contrast with healthy ground stiffness as $7000\text{MPa}$. In addition, the loss factor for damping of the defect is as twice that of normal material. The estimated imaginary part of wave number-frequency curves by both ground acceleration
and acoustic pressure are given in Fig. 5-13. In contrast with healthy homogeneous half-
space, the dispersion of imaginary part of wave number within 5kHz range presents a valley
centering around the vertical line which implies the theoretical depth from 0.5m to 1m of
the defect. For both ground acceleration and acoustic pressure, this difference could
identify the existence of the hidden defect.

![Figure 5-13 Imaginary part of wave number dispersion (Case 4)](image)

(e). **Half-space with descending stiffness along depth (Case 5)**

One more situation is studied with FEA synthetic signals where the stiffness of solid half-
space decreased exponentially with the depth continuously as Eq. 5.2.13. The simulated
experimental configuration is the same as Fig. 5-6(a), but with descending stiffness along
depth.

\[ E = E_0 e^{a_0 d_1} \quad (5.2.13) \]

Where, \( E_0 \) is taken as 7000MPa, \( a_0 \) taken as -1 while depth \( d_1 \) from 0 to 1m. The empirical
shear velocity-depth curves through both ground acceleration and 0.02m high microphones
are compared as Fig. 5-14. The shear velocity decreases with depth stably as expected. This
Northeastern University | 91

案 illuminates the flexibility and potential to expand the proposed method from homogeneous structures or superposed homogeneous structures into inhomogeneous structures.

![Graph](image)

Figure 5-14 Empirical inversion (Case 5)

(f). Field test at NCAT (National Center of Asphalt Technology)

In addition to typical cases studied with synthetic surface wave signals, field test data is also analyzed with proposed method. The field test has been done at the special test lane at NCAT (National Center of Asphalt Technology) where the profile of the top pavement layers is documented as design. Fig. 5-15 shows the test configuration, where Measurement Specialties 7105A accelerometers and G.R.A.S. Directional microphone 40AE are used. The impact source-receiver and receiver-receiver distances are 16 inches. The designed profile of the pavement segment is as Table 5-4.
Table 5-4 Profile of pavement segment as design

<table>
<thead>
<tr>
<th>Top: 2-inch lift</th>
<th>Full bond</th>
<th>HMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom: 3-inch lift</td>
<td>Full bond</td>
<td>HMA</td>
</tr>
<tr>
<td>Existing surface</td>
<td>PCC</td>
<td>PCC</td>
</tr>
</tbody>
</table>

Figure 5-15 Test configuration at NCAT and pavement profile as design

The dispersion curve of phase velocity through accelerometers is presented in Fig. 5-16(a) to investigate the pavement profile at NCAT. The vertical straight line indicates the frequency that the subsurface material changes from HMA (Hot Mix Asphalt) to PCC (Portland Cement Concrete) at 5 inches depth (Table 5-4). The estimated dispersion curve has a dramatic sharp drop at that frequency, which could identify the layer bonding between different materials. The phase velocity increases sharply as the frequency passes 1500Hz (hinted by vertical line) to the lower band, which matches the stiffness enhancement from HMA to PCC. The full bonding between the same materials (HMA) at 2 inches depth is
not identified due to the healthy bonding situation within uniform material. In contrast to traditional SASW, the proposed method also estimates the imaginary part of wave number using a limited number of receivers (three in this case). A similar sharp and deep valley could be identified on the curve of dispersion of imaginary part of wave number, where the layer bonding at a 5 inch depth is hinted with vertical line (Fig. 5-16 (b)). When the ratio of the imaginary part over real part of wave number is normalized, the curve implies the layer bonding depth clearly, as shown in Fig. 5-16(c). There exists a step around 1500 Hz (indicated by a vertical line). The normalized ratio before the sharp step drop bounces around 0.74 (dashed horizontal line) while this ratio curve is around 0.15 (dashed horizontal line) after the step drop. In this case, the averaged step-like curve (dashed horizontal line) changes by a roughly a factor of 5 from high step to low step. In contrast with the phase velocity dispersion curve, the dispersion of the imaginary part of wave number and normalized ratio of imaginary over real part of wave number is more sensitive to material change. Similarly, but using a microphone array instead, a normalized ratio of imaginary part over real part of wave number curve as Fig. 5-16(d) could indicate the layer bonding depth (2 inches above the accelerometer array).

The wave number estimation method was proposed in this chapter. It approximates the measured wave field through exponential fitting in complex wave number domain. The requirement for amount of sensing channel is reduced compared to the multiple channel f-k method and MASW method. The phase velocity of the homogeneous half-space coincides with the analytic results accurately by a forward modeling. The comparison with principal SASW shows enhanced measurement for the dispersion curve. The empirical inversion of shear velocity could characterize the subsurface profile. Additionally, field
test at NCAT demonstrates the capability of proposed method to assess the subsurface features of elastic structure such as pavement. With the help of wave number estimation method, a confident dispersion curve is ready for followed inversion analysis, which tried to back-calculate the subsurface profile of ground.

Figure 5-16 (a) Dispersion curve (b) imaginary part of wave number (c) normalized ratio: Im(k)/Re(k) by acceleration (d) normalized ratio: Im(k)/Re(k) by acoustic pressure.
6 INVERSION OF SURFACE WAVE BASED METHODS

6.1 Brief Review of Current Methods

One major issue that restricts the efficiency of SASW and related surface wave method is the iterative inversion process, which is usually time consuming and requires expertise to initialize the profile. Consequently, the SASW method is implemented as a point-to-point, post-processed, stationary test. Researchers are seeking faster and automated inversion algorithms to advance its efficiency. An algorithm was developed in 1995 to construct the dispersion curve rapidly through fitting a complex-valued curve to the phase information of the cross power spectra using coherence function as weighting function (Nazarian, et al. 1995). A Monte Carlo algorithm and the maximum likelihood method were chosen respectively to examine the possible solutions with minimal constraints and to estimate the uncertainties of the resulting model parameters (Orozco, 2003). In order to identify the predominant propagation modes easily, an inversion method based on the maximum vertical flexibility coefficient was introduced (Zomorodian, et al. 2006). In addition, a new algorithm called peak-through and frequency-wave number (PT/FW) technique was developed in 2006 to determine the phase velocity more effectively instead of the traditional phase difference method (Joh, et al. 2006). Moreover, genetic algorithm (GA) based inversion (Pezeshk, et al. 2005) and combination of genetic and linearized algorithms in a two-step joint inversion (Picozzi, et al. 2007) have been employed in recent years. Ryden et al. (2006) proposed a global search algorithm to invert the complete phase-
velocity spectrum based on fast simulated annealing (FSA). All these efforts drove the inversion for better certainty with various mechanisms.

6.2 Difficulties for Current Methods

Due to the complexity of inversion, there are difficulties for existing methods. For genetic algorithm (GA) and artificial neural network (ANN) methods, the common issue is the requirement of substantial training to build up the intelligent network. This would require a database of pavement models by forward modeling to offer training data. Thus, the drawback of this kind of method is the significant preparation needed to form the aforementioned database.

Monte Carlo based methods, including the simplex method, have the benefit of being comparatively fast and simple. However, the difficulty lies within the uncertainty of the wave mode. It is easy to mismatch the measured dispersion curve to a forward modeled curve based on an incorrect wave mode. The other drawback is the tedious trial-error iteration needed to match the measured and forward modeled dispersion curves, which could be low efficiency due to time-consuming forward modeling.

Stimulated Annealing (SA) and Fast Stimulated Annealing (FSA) are good solutions to multi-mode matching in the whole phase-velocity spectrum in a global optimization way. It is an alternative solution to the complicated inverse multi-mode dispersion curve from pavement measurement. However, these methods still exhibit the drawback of being computationally burdensome for acceptable accuracy (Ryden et al., 2006).
6.3  In-Situ Particle Displacement Based Fast Inversion

The above existing methods have a shared disadvantage of being time consuming, caused by either tedious forward modeling for trial-error iteration or complicated matching between the measured and forward modeled dispersion curves. Inspired by the efficiency issue, an inversion algorithm is proposed to provide fast implementation. The in situ particle displacement attenuation distribution, in conjunction with penetration depth, is found to dominate the relationship between the shear velocity profile and the dispersion curve. Therefore, the phase velocity of a certain wavelength is expressed as a weighted combination of shear velocities within the penetrating depth, where the normalized particle displacements are used as the weighting coefficients. The proposed algorithm does not require manual input or adjustment of trial profiles, as neither the forward modeling nor the stiffness matrix is needed. Thus, it is fully automated, which increases the speed of air-coupled surface wave methods to that of a quasi-real-time mode.

(1). In situ particle displacement of surface wave

A fundamental feature of surface waves is the shape of their wavefronts. It has been discovered the surface wave propagates radially outward along a cylindrical wavefront, while the P- and S-waves propagate along a hemispherical wavefront. This means that within the penetrating depth, surfaces waves propagate outward at the same velocity as P- and S-waves.

On the other hand, particle motion of a surface wave varies along the penetrating depth and becomes small at depths of approximately three times the wavelength. Barkan (1962) gave
the approximate solution to the particle displacement of a surface wave along with the penetrating depth as:

For Poisson’s ratio $\nu=0.5$:

$$
\begin{align*}
\frac{u(y)}{L_c} &= (-0.1298e^{\frac{2\pi y}{L_c}} + 0.0706e^{\frac{0.2958}{2\pi y}}) \frac{P}{\mu} \\
\frac{v(y)}{L_c} &= (0.1298e^{\frac{2\pi y}{L_c}} - 0.2387e^{\frac{0.2958}{2\pi y}}) \frac{P}{\mu}
\end{align*}
$$

(6.3.1)

For Poisson’s ratio $\nu=0.25$:

$$
\begin{align*}
\frac{u(y)}{L_c} &= (-0.2958e^{\frac{(0.8474)2\pi y}{L_c}} + 0.1707e^{\frac{(0.3933)2\pi y}{L_c}}) \frac{P}{\mu} \\
\frac{v(y)}{L_c} &= (0.2507e^{\frac{(0.8474)2\pi y}{L_c}} - 0.4341e^{\frac{(0.3933)2\pi y}{L_c}}) \frac{P}{\mu}
\end{align*}
$$

(6.3.2)

Where $u$ and $v$ are the horizontal and vertical components of the amplitude of particle displacement, respectively; $L_c$ is the wavelength; $y$ is the depth; $y/L_c$ is the dimensionless depth; $\mu$ is the Lamé coefficient (shear modulus); and $p$ is the impact force.

When replacing $u$ and $v$ with the dimensionless displacements as $u/u_0$ and $v/v_0$, respectively ($u_0$ and $v_0$ are the displacement at the surface), the distribution of particle displacement amplitude can be plotted in a graph with the dimensionless displacement vs. dimensionless depth, as shown in Fig. 6-1. This ensures the effect of various values of Poisson’s ratio on particle displacement is negligible.
Figure 6-1 Distribution of particle displacement along with penetrating depth of surface wave

(2). Relationship between phase velocity and shear velocities of layered system

For a layered ground system, surface wave wavefronts should remain cylindrical during propagation if the fundamental mode is dominant and multi-mode effects are negligible. Therefore, it is reasonable to assume that a similar linear relationship still exists between the phase and shear velocities of the underground layers. Since the wave in the penetrated layers travel with the same wave number, it is probable that some kind of average of the shear velocities of these layers dominates the phase velocity. This assumption was confirmed by the research of Xia et al. (1999) that discovered that compared to P-wave velocity, density, and layer thickness, the shear wave velocity is the dominant parameter influencing changes in Rayleigh-wave phase velocity in the high-frequency range (>5 Hz) (Xia et al., 1999). Moreover, from an energy point of view, the particle vibrating with a larger displacement must contribute more to the velocity of the entire surface wave. Therefore, the distribution of particle displacement along penetrating depth would be chosen as the weighting factor of the averaging. Since SASW
Northeastern University | 100

sensors only measure the vertical component of surface wave displacement, only the vertical component of particle displacement contributes to the weighting factors. Thus, a weighted averaging relationship is proposed herein to directly connect the phase velocity and the layer shear velocities (Cao et al., 2011).

(3). Inversion algorithm

With the relationship revealed above, it is very easy to obtain the estimated phase velocity of a surface wave for a certain system with a given layer profile. A new inversion algorithm can be established to estimate the layer profile from the measured dispersion curve with SASW tests. The new algorithm consists of two stages: Initializing and iterative adjusting.

Stage one as initializing: 1) Given a dispersion curve in a function of phase velocity vs. wavelength; 2) Convert it to a discrete function of phase velocity vs. approximate layer depth, using the empirical depth to wavelength ratio 0.3-0.4; 3) Assume each depth indicates a layer; 4) Starting from the first layer, assume the entire structure as a half-space, then the shear velocity of the first layer $V_s^0(1)$ can be solved; 5) Go to the second layer, assume the second layer together with under-layers are one single half-space, then solve the initial value of shear velocity for the second layer $V_s^0(2)$; 6) Step forward and solve initial shear velocities for the rest of discretized layers.

Stage two as iterative adjusting: 1) Starting from the second layer, leave the second layer shear velocity $V_s^1(2)$ unknown, solve the $V_s^3(2)$ from above equations using the previously obtained shear velocities of all other layers; 2) Calculate the difference $R_2 = V_s^3(2) - V_s^0(2)$; 3) Adjust the shear velocity of the second layer $V_s^1(2)$ by the 20% or less of $R_2$ for better
convergence, that is $V_s^2(2) = V_s^0(2) + 0.2 R_2$; 4) Step forward and solve new values for all layers; 5) Repeat steps 1) to 4) until the solutions converge.

In the inversion, each step of a discrete dispersion point is regarded as a thin layer; the inversion method does not determine the actual layers and depths directly. The actual layers and depths can be observed from the inverted shear velocity profile. As long as the inversion is correct, those thin layers that belong to an actual layer should have a very similar shear velocity in the inverted profile. Since prior assumption of layer depth is not needed, this inversion produces unique solution. In contrast, the conventional inversion methods are sensitive to the pre-assumed initial shear velocity profile and consequently often produce multiple valid solutions.

Fig. 6-2 shows the logical flowchart of the above two inversion stages. It can be seen that all calculations in the inversion are purely algebraic operations for a given discrete dispersion curve; no differential equations are involved. Therefore, the entire inversion procedure is extremely fast and fully automated in comparison with the traditional inversion procedures. It takes less than 1 second to calculate the inverted shear velocity profile using a Matlab script developed according to the above algorithm.
Validation and application

(a). Stiffness matrix forward model

As compared to the traditional derivation of a dispersion curve using differential equations in solid mechanics, the proposed shear-dispersion relationship and corresponding inversion algorithm is rather simple. It focuses on the dominant features of wave propagation and neglects many other physical components. Therefore, it is virtually an empirical simplification of dispersion/inversion analysis. To date, no mathematic validation has been derived for this algorithm. Instead, the numerical forward simulation based on the stiffness
matrix method is selected as a trustworthy tool to validate the accuracy of the fast inversion method.

(a1) Ascending Stiffness Profile

A layered structure with ascending shear velocities along depth is selected to simulate a typical geological site. In this scenario, layer stiffness increases with depth. Two softer layers are sitting on the harder infinite half-space soil. Table 6-1 shows the layer configuration and material properties. A forward simulation program based on stiffness matrix method is developed to analyze wave propagation. The calculated dispersion curve is compared to the result from Zomorodian et al. (2006), who used identical profile configurations. Fig. 6-3 shows the forward simulation of dispersion curve by stiffness matrix method. It can be verified the dispersion curve in Fig. 6-3 using the program developed by the author matches with the dominant fundamental mode of the published curve in Fig. 6(a) by Zomorodian et al. (2006) exactly. Thus, the calculated dispersion curve in this dissertation is accurate.

Table 6-1 Layered structure with ascending velocity profile

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>Damping ratio</th>
<th>Poisson's ratio</th>
<th>Density</th>
<th>Shear velocity</th>
<th>Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20m</td>
<td>0.005</td>
<td>0.35</td>
<td>20kN/m³</td>
<td>300m/s</td>
<td>495MPa</td>
</tr>
<tr>
<td>2</td>
<td>20m</td>
<td>0.005</td>
<td>0.35</td>
<td>20kN/m³</td>
<td>500m/s</td>
<td>1376MPa</td>
</tr>
<tr>
<td>3</td>
<td>infinite</td>
<td>0.005</td>
<td>0.35</td>
<td>20kN/m³</td>
<td>700m/s</td>
<td>2698MPa</td>
</tr>
</tbody>
</table>
Based on the analytical dispersion curve by stiffness matrix method, the shear velocity profile is estimated using the proposed fast inversion algorithm. The inversion calculation is finished extremely fast (less than 1 second). The results are compared with the given profile in Fig. 6-4. It can be seen from the Fig. 6-4(a) that the inverted shear velocity profile follows the overall trend of the original profile and matches the value best at the top layer and infinite layer. It is also shown from the figure that the inverted layer depths are not at the same with the original because the inversion method automatically takes the data points at dispersion curve as thin layers by discretization. A better comparison is made by averaging the inverted shear velocity profile in the same depths of original profile, as shown in Fig. 6-4(b). It can be seen from the averaged comparison that results for the top and infinite layers have best accuracy and middle layer has lowest accuracy.

Figure 6-3 Analytical dispersion curve (dominant mode)
(a) Inverted shear profile  
(b) Averaged shear profile

Figure 6-4 Inverted shear velocity profile vs. original profile for ascending stiffness profile

(a2). Descending Stiffness Profile and Limitations

A layered structure with descending shear velocities along depths is selected to simulate the typical pavement structure. Two harder layers are sitting on the softer infinite half-space soil. Table 6-2 shows the layer configuration and material properties.

Table 6-2 Layered structure with descending velocity profile

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>Damping ratio</th>
<th>Poisson’s ratio</th>
<th>Density</th>
<th>Shear velocity</th>
<th>Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2m</td>
<td>0.005</td>
<td>0.35</td>
<td>20kN/m³</td>
<td>2000m/s</td>
<td>22025MPa</td>
</tr>
<tr>
<td>2</td>
<td>0.3m</td>
<td>0.005</td>
<td>0.35</td>
<td>20kN/m³</td>
<td>1000m/s</td>
<td>5506MPa</td>
</tr>
<tr>
<td>3</td>
<td>infinite</td>
<td>0.005</td>
<td>0.35</td>
<td>20kN/m³</td>
<td>700m/s</td>
<td>2698MPa</td>
</tr>
</tbody>
</table>

Fig. 6-5 shows the calculated analytical dispersion curve and inverted shear velocity profile, in comparison with the original profile in same depths. Due to the multi-mode reflection in the top layers, the higher modes were extracted in the dispersion analysis. Since the proposed inversion is based on the assumption that the fundamental mode is apparent and dominant with homogeneous half-space or ascending stiffness profile, the phase velocity at higher modes needs to be excluded before the inversion analysis to avoid errors. After
excluding the dominant higher modes, the comparison in the Fig. 6-5(b) shows that the inverted shear velocity profile approximates the original profile, with the exception the top layer.

(a) Analytical dispersion curve                   (b) Inverted averaged shear profile

Figure 6-5 Inverted shear velocity profile vs. original profile for descending stiffness profile

(b). Comparison with other methods

For a comparison to other methods, an example is selected from the research report by Nazarian et al. (1985). A geological field was tested with the SASW method. The dispersion curve was generated according to phase difference between two geophones. The inversion process was based on the iterative guess-and-check strategy with forward analytical analysis. Dunkin’s extension of Haskell-Thomas’s approach (Dunkin, 1965) was used as the forward analytical approach.

The dispersion curve in Fig. 6-6 is measured from the report (Nazarian et al., 1985) and used as the dispersion curve input of the proposed inversion algorithm. The new estimated shear velocity profile is also plotted in Fig. 6-6 in comparison with the reported estimation.
It can be seen in Fig. 6-6(a) that the automatically generated shear velocity profile has more detail layer classifications. In order to make a better comparison to the reported result, the estimated profile is averaged according to the same depths as the report, as shown in Fig. 6-6(b). According to Fig. 6-6(b), the estimated profile and reported profile are close to each other well.

Figure 6-6 Estimated shear velocity profiles using the proposed inversion algorithm

(Vertical axis scale is wavelength for dispersion curve and depth for profile)

6.4 **Lamb Wave Based Inversion for Stiff Top Layers Profile**

When the traditional SASW method is used on pavement structures, some difficulties would arise. One critical issue is the accuracy requirement for pavement inspection. The early SASW method emphasized larger scales and deeper investigation depths, such as found in geological sites. In this case, generally, the accuracy of the inversion is not great.
this is particularly true with comparatively large layer numbers of large-scale layer thicknesses. However, when the tested object is a pavement structure, the accuracy becomes a focus for the inversion since the layer thickness is small, on the scale of inches to tens of inches. The other critical issue is the multi-mode effects due to the highway pavement structure features. When layer stiffness increases with depth, the Rayleigh wave fundamental mode is the dominant mode in the entire frequency range, which satisfies most geological tests (Zomorodian et al., 2006). But for highway concrete pavement structures, the top layer is often stiffer than beneath layers and the stiffness contrast between layers could be large (Papagiannakis et al. 2008). Thus, multiple-mode effects must be considered when the inversion is processed. Otherwise, the inversion result would deviate from the actual profile if only the fundamental mode were considered.

When a pavement structure with a stiff top layer has a large stiffness contrast that decreases with depth, the superposed dispersion curve formed by dominant modes at corresponding frequencies is guided and constrained by the fundamental antisymmetric (A0) mode of Lamb wave in top layer as free plate (Fig. 6-7). It could be explained by the wave number continuity requirement along the layer interface. When the second layer shear velocity is smaller than top layer, only the higher Lamb wave modes in the slower layer are able to meet the A0 mode in the top layer with larger shear velocity. This principle makes the A0 mode of Lamb wave in the stiff top layer become the predominant mode in the whole frequency range. Therefore, as in Fig. 6-7, the three-layered pavement structure (Fig. 6-7(a)) would behave very similarly to a free plate as the stiff top plate (Fig. 6-7(b)).

Recent research efforts on the surface wave method for pavement have emphasized the effects of multiple modes and explained the dominant dispersion curve by quasi-Lamb
waves in stiff top layers (Ryden et al., 2004). Ryden and Lowe theoretically explained this principle by a wave propagation model (Lowe et al., 1995).

Fig. 6-8 illustrates one model for a typical flexible pavement with a stiff top layer. For this pavement profile, the stiffness decreases as shear wave velocity decreases with depth, meanwhile the top layer exhibits a comparatively large stiffness as a solid top shell.
The antisymmetric and symmetric Lamb wave modes of the above pavement model were determined by the eigenvalues of the stiffness matrix, as formed using the stiffness matrix method. The modes are presented as A0, A1, A2 and S0, S1, in Fig. 6-9. It is observed that the dominant mode (circles) is a jumping track mainly following A0, which is the fundamental antisymmetric Lamb wave of the top layer.

Figure 6-9 Pavement dispersion fitting inversion by Lamb wave modes

Naturally, when the top stiff layer A0 dispersion information is applied, the difficulties of multiple modes from pavement structure would become apparent. Through applying the NMSE (normalized mean square error) searching algorithm, the measured (or numerical simulated) dispersion curve would be tried to fit with the A0 mode curve to find the top layer, then searching the underneath layer. Following the pavement profile as Fig. 6-8, the
Lamb wave based inversion presents an accurate profile result for such a pavement model as Fig. 6-10, especially for the stiff top layer, which exhibits a dominant A0 mode.

This chapter introduced the current surface wave inversion methods and corresponding limitations. The in-situ particle displacement based fast inversion method was proposed to achieve a high efficiency inversion calculation. It was validated with the stiffness matrix method and other published works for regular profile or when the stiffness differences are not large. The method has the limitation of relying on the fundamental mode; if the top layer is relatively stiff, the mode jumps out of the fundamental. In this case, a Lamb wave based inversion method was proposed to solve the stiff top layer by fitting the Lamb wave A0 mode to the measured dominant dispersion curve. Based on these findings and methodologies, implementation for field-testing was realized through the development of the Mobile Acoustic Subsurface Sensing (MASS) system in the following chapter.
7 DEVELOPMENT OF MOBILE ACOUSTIC SUBSURFACE SENSING (MASS) SYSTEM

7.1 Non-Contacting Sensing with Microphone

For decades, low efficiency has been a drawback for contact sensing methods due to the cost and time of sensor repositioning. Traditional SASW, f-k methods, and so on suffer the tedious pasting step for attaching either an accelerometer or geophone to the ground. Due to the recognition that surface waves radiate acoustic waves, efforts to replace vibration sensors with acoustic sensors have been underway for some time with the goal of increasing scanning efficiency. Some earlier efforts, for example, include Moore's (1973) work to detect the subsurface defects on the bridge deck with acoustics. Recently, Zhu et al. (2002; 2008), investigated the acoustic sensing approach and application for surface waves. Their work demonstrated that the surface wave could be measured with radiating sound pressure similarly to the acceleration or velocity of the structure response. Other works to diagnose pavement subsurface profiles with mobile acoustic sensing facilities were introduced by Ryden et al. (2007; 2008) and Marzani et al.(2004). All these efforts extended the surface wave method to a non-contact acoustic sensing direction.

7.2 The Hardware Prototype Design

7.2.1 The Mobile Platform and Data Acquisition Deployment

To implement the rapid subsurface NDT of the road by acoustics, a mobile platform prototype, known as the Mobile Acoustic Subsurface Sensing (MASS) system has been
designed and assembled as Lu et al. (2013). The early version of MASS has been built up on a 4-wheeled cart with a beam expansion as sensing array (Fig. 7-1). Fig. 7-2 presents the field test by the early version of MASS. It had some drawbacks such as unstable cart framework and cantilever beam mounting of the impactor. Design improvements were made to develop the next generation MASS. The current MASS is constructed on a 3-wheeled cart as Fig. 7-3. The cart platform is designed with an emphasis on stability during movement and damped impactor mounting. The MASS and its subsystems are presented in Fig. 7-3.

Figure 7-1 Early version of MASS design
Figure 7-2 Field test with early version of MASS

Figure 7-3 Integration of hardware of MASS
The first critical subsystem is the electronic hammer subsystem indicated as (a) in Fig. 7-3. The details of the design are addressed in the subsequent section. The microphone array is as Fig. 7-3(b); the height is adjustable to allow for robust sensing of road surface variations. The array beam is also isolated with damper to minimize the transmission of vibrations from the cart. The distance register (Fig. 7-3(c)), performs the registry of location and triggers the system by distance setting.

The MASS DAQ consists of a signal conditioner, a DAQ motherboard, a Single Board Computer (SBC), DC power converter, and solid state hard drive. The DAQ subsystem is enclosed as shown in Fig. 7-3(d). In the system, a SCM5B48 unit is selected as the signal conditioner. The PC104P-24DSI12 is selected as a 12-channel DAQ board, which features low noise, 24-bit resolution, low phase distortion, and multi-board synchronization. An embedded single board computer (SBC) called Mamba from Versalogic (Tualatin, OR, USA) with a high-performance Intel Core 2 Duo processor, computes at up to 2.26 GHz. The Operation System is QNX. The system has multiple input channels with high sampling rate up to 200kHz.

![Figure 7-4 DAQ communication architecture](image)
7.2.2 Impact Source with Electromagnetic Hammer

The traditional operation of surface wave based method usually needs a manual hammer as the impact source to excite the wave. The issue of this implementation is the stability and repeatability due to the operator. In order to make a mobile machine to excite the surface wave stably, an electromagnetic hammer is designed.

The electromagnetic hammer unit was assembled from two solenoid linear actors (Amenity-40ps), as shown in Fig. 7-5(a). The hammer unit is controlled with two time relay delay units (528-TDRSOXP-24V); the power is shifted from the lift solenoid (which locates on top) to the shoot solenoid (which locates on the bottom). In this case, the hammer core would be lifted to the optimal position ready to be shot down with large impact force. The impact duration could be controlled with the time relay delay.

To supply broad band transient impacts on the pavement and study their effects on the results, a professional shock accelerometer is screwed on top of an extension aluminum
Northeastern University | 117

bar embedded with magnetic steel core co-axially (Fig. 7-5(b)). Additionally, the hammer tip was designed to be replaceable and a series of tips could be installed on the end of hammer core to supply different impact characteristics (Fig. 7-5(c)).

The working height of the EM hammer is adjusted with a shifter unit (TCI 748000 shifter). When MASS cart is moving between impact points, the EM hammer is lifted to a higher elevation for protection (Fig. 7-6(a)). An integrated control box was built to cover the control circuitry and cable connections, as shown in Fig. 7-6(b). The data trigger was selected as the lift solenoid power to initiate the data acquisition.

![Figure 7-6 Hammer control unit](image)

(a) Control handle  (b) Control circuit box

Figure 7-6 Hammer control unit

7.2.3 Sound Enclosure and Reflection-Free Design

The sound enclosure for the microphone was introduced in Chapter 4, section 4.4.1. Specific details could be found there. In addition to the sound enclosure, the cart is also equipped with a sound absorbing layer on the chassis (Fig. 7-3(h)). This pyramid shape would guide the incidence wave to reflect and decay within the wedge angle zone to absorb the wave from the ground. In this case, the reflection under the cart chassis is mitigated.
7.2.4 Distance Trigger Data Registration

The distance encoder/register subsystem (Fig. 7-3(c)) is assembled with encoder mounted on the rear wheel and a PLC control unit (Fig. 7-3(c)). The sensing spatial resolution is adjustable by changing the parameter setting at the PLC unit. Through this design, the system could operate the impact and collect signals automatically when the operator is pushing the cart as Fig. 7-7.

![Figure 7-7 Automatic operation by distance trigger](image_url)

7.3 The Software Framework Design

The MASS software framework consists of three modules: (1) the data acquisition program under QNX operating system which sets up the sampling configuration; (2) a fast air-coupled SASW analysis program under the MATLAB framework in the laptop; and (3) the real-time data communication between the DAQ and laptop.

One benefit of this design is that the convenient MATLAB programming environment is robust enough for the analysis program updating for the prototype development. Consequently, the architecture of hardware and software integration is shown in Fig. 7-8.
7.4 Field Test and Analysis

The MASS system was field tested with the goals of rapidly studying the road subsurface, as well as to discover possible limitations for future design modifications.

7.4.1 Asphalt Pavement

The MASS system was tested on an asphalt pavement located near the Northeastern University campus. The testing path was along a white chalk line as shown in Fig. 7-9(a). The testing configuration is shown in Fig. 7-9(b), where the microphone enclosure is 1 cm above the ground while the near (channel A) and far (channel B) microphones are 20 cm and 60 cm apart from the impact source, respectively. The sampling rate is set as 200 kHz for all sensing channels, such as the microphones and hammer accelerometer. After set-up, the entire system could be operated by only one person at walking speed.
Figure 7-9 Test on asphalt pavement. (a) Mobile sensing with MASS. (b) Test configuration

A typical testing point result is shown in Fig. 7-10. After software pre-processing, with the denoising sound enclosure as mentioned in Chapter 4, the radiating surface wave is extracted. Fig. 7-10(a) indicates that the extracted signals are clean and smooth. The inversion result to indicate the stiffness profile is shown in Fig. 7-10(b). Without prior information about the paving material, a uniform mass density of 1,800 kg/m³ and a Poisson’s ratio of 0.3 are assumed in the calculation of the elastic modulus as general civil material properties. According to the profile, the first asphalt layer has an estimated depth of 0.1 m (3.94 inches) and estimated elastic modulus of 6.5 GPa (942.7 ksi), which falls into the range of a regular asphalt concrete material from 4.4 GPa (638.2 ksi) to 6.8 GPa (986.3 ksi). Also, the thickness of the top layer matches with the typical roadway paving design. Underneath the top layer, the stiffness apparently decreases, as the modulus approaches 0.218 GPa (31.6 ksi) at around 0.4 m (15.7 inches) in depth. This is estimated to be compacted soil material.
7.4.2 Concrete Slab

The MASS system was also tested on a concrete slab in the Laboratory for Structural Testing of Resilient and Sustainable Systems (STReSS Lab) at George J. Kostas Research Institute for Homeland Security at Northeastern University. The same test configurations as above are employed. Fig. 7-11(a) records the test scenario, where the MASS cart is working in the central area of the slab in order to avoid the reflections of the stress waves due to the limited slab size. The cross-section of the slab is photographed as Fig. 7-11(b), with a symbolic diagram underside. The slab is embedded with two rows of metal rebar located 8.9 cm (3.5 inches) below the surface for the top row while the bottom row is close to the bottom surface. The thickness of the slab is 20.32 cm (8 inches).
The testing results are presented in Fig. 7-12. The extracted radiating surface wave is presented in Fig 7-12(a), where the signals are clean enough for post-processing after pre-processing as mentioned in sections 3.2 and 3.3. As compared to the radiating surface wave extracted from the asphalt pavement shown in Fig. 7-10(a), the signals coming from the stiff concrete slab present fluctuations with higher frequencies. When the stiffness of the top layer is much larger than that of the sub-grades underneath, the surface wave approaches the Rayleigh-Lamb wave. Without using multiple-channel sensing to resolve the higher modes, the fast air-coupled SASW procedure with only two channels still offers an acceptable estimation of the profile as seen in Fig 7-12(b). The estimated total thickness of around 20.32 cm (8 inches) matches with the actual thickness (Fig. 7-11(b)). The average elastic modulus of the concrete slab is estimated as 11.9 GPa (1,720 ksi). This modulus estimation is within the accepted normal concrete slab modulus range and is a little lower than average. The minimum stiffness of 2.1 GPa (300 ksi) that is indicated slightly below the slab thickness could be caused by the wood beam foundation (Fig. 7-11(a)). Due to the large stiffness contrast between concrete slab and the wood beam foundation, the deeper profile of
the lab ground would not be identified from Fig. 7-12(b). This test demonstrates the capability of the MASS system for floating style concrete slab sensing through acoustics.

Figure 7-12 Concrete slab test results. (a) Extracted radiating surface wave. (b) Estimated elastic modulus profile

7.4.3 Concrete Bridge Deck

Aside from the capability for sensing pavement structures, the MASS system has the potential for bridge deck structure sensing. The fast air-coupled surface wave analysis program could be used for the bridge deck test with a Lamb wave inversion when the half-space foundation is deleted. The MASS system tests were performed on a bridge deck on the Pingree Bridge (Pingree Farm Rd, Rowley, MA, USA). The bridge consists of single layer concrete deck with as designed 9 inch thickness and spans around 240 ft above the Interstate 95 highway (Fig. 7-13(a)).

The test is implemented in the real traffic environment with traffic noise. The MASS system configuration is maintained the same as in the preceding tests. The scanning is executed along a path (the red dotted line with arrow in Fig. 7-13(a)) where no support
beam is present underneath. The continuous scanning test results are presented in Fig. 7-14. In total, 23 test points are scanned with 1.22 m (4 ft) spacing along the scanning path. Fig. 7-14(a) shows the filtered acoustic signals in the form of the extracted radiating surface wave. It could be observed that the signal features are close to those of the concrete slab as in the previous case. Higher frequency signal components are apparent. The successive profiles acquired through the mobile scanning at a walking speed are summarized in Fig. 7-14(c). The results are consistent along the same path and the estimated thickness and close to the designed thickness at 0.23 m (9 inches) (red star line in Fig. 7-14(c)). The averaged modulus of the deck is 17.7 GPa (2580 ksi). The profile at the 20th, 21st and 22nd points give an abnormally low modulus around 2.7 GPa (400 ksi). This abnormality is caused by passing over the slab joint crack as shown in Fig. 7-14(b). The slab joint crack can be identified readily. This fieldwork test verifies the potential for bridge deck testing using the MASS system, which is designed originally for pavement structures, when some modifications are made to the program.

![Figure 7-13 Pingree bridge deck test (Rowley, MA). (a) Scanning path on bridge deck. (b) MASS operation on bridge deck](image)
In this chapter, a mobile acoustic testing system was developed to estimate the subsurface profiles for both the thickness and stiffness of layers. The air-coupled non-contact sensing strategy is adopted in the MASS development. The integration of the hardware utilizes the distance register/trigger together with an electronic hammer as impact source to supply automatic excitation. The de-noising sound enclosure and vibration isolation design improve the feasibility of acoustic sensing in actual fieldwork. The prototype hardware and software combination was demonstrated in the field test for this concept. Despite these achievements, development of MASS is ongoing. A better impulse mechanism is needed to give the stable wave stimulation. Meanwhile, some post-processing methods may be
used to compensate for the statistical randomness and non-homogeneity of civil material. Additionally, more efficient de-noising devices are also being researched to supply even cleaner and higher signal to noise ratios for acoustic sensing under heavy traffic noise conditions.
8 TIRE EXCITED ELASTIC WAVES OPPORTUNITY FOR SUBSURFACE CHARACTERIZATION

8.1 Modeling Pavement Acoustic Response from Tire Loading

A multiple layered pavement structure usually has a stiff top layer which dominates ground vibration by flexural waves excited from traffic loading. With regards to this fact, a simplified model of pavement was proposed by using the classic plate model to demonstrate the apparent/general stiffness and the corresponding response of pavement.

Tire loading was considered as a concentrated point load onto the elastic plate as ground. A schematic of this is shown as Fig. 8-1.

Figure 8-1 Schematic of tire loading model
When tire loading is considered as a concentrated point load, it would apply to the classic elastic plate vibration as

\[ D \left( \frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right) + \rho h \ddot{w} + sw = f(x, y, t) \quad (8.1.1) \]

With \( D \) as the bending rigidity; \( w \) as vibration displacement; \( x, y \) are the coordinates of point load on the plate; \( \rho \) as the density of plate; \( h \) as the thickness of plate; \( s \) as the Stiffness of Winkler foundation.

The harmonic time dependence \( f(x, y, t) \) and \( w(x, y, t) \) could be expressed in the frequency domain as

\[ f(x, y, t) = \Re \{ \tilde{f}(x, y) \exp(i\omega t) \} \quad (8.1.2) \]

\[ w(x, y, t) = \Re \{ \tilde{w}(x, y) \exp(i\omega t) \} \quad (8.1.3) \]

The concentrated point load representing the tire could be written as Dirac delta function for its coordinates on the plate.

\[ \tilde{f}(x, y) = f_0 \delta(x) \delta(y) \quad (8.1.4) \]

The solution of vibrational response as displacement is

\[ \frac{\tilde{w}}{f_0} = \frac{-i}{8Dk_f^2} \left( H_0^2(k_f r) - i \frac{2}{\pi} K_0(k_f r) \right) \quad (8.1.5) \]

Where the flexural wavenumber equals
After solving the ground vibrational response, the acoustic radiating could be calculated with Rayleigh’s Second Integral.

\[
p(x, y, z) = -i \omega p \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} v(x', y') \frac{e^{i \omega R}}{2\pi R} dx' dy'
\]

(8.1.7)

Where \( p \) is the radiating acoustic pressure, \( v \) is the vibration velocity, \( R \) is the distance from the load point to the receiver as Fig. 8-2.

![Figure 8-2 Coordinates of source and receiver positions](image)

If the vehicle underbody is considered for its acoustic image reflection, the sound source will be treated as Fig. 8-3.

![Figure 8-3 Underbody sound image](image)
The above procedure is focused on single concentrated point load, for a vehicle with multiple tires, for example, four tires, linear superposition could be used to expect the wave field of acoustic radiation from the whole vehicle. The corresponding coordinates of footprints of the vehicle tires would be used for the $R$ as Eq. 8.1.7. For a typical pavement profile from Ryden and Lowe (2004), the top layer is used for the plate model parameters as Table 8-1.

Table 8-1 Pavement model profile

<table>
<thead>
<tr>
<th>Layer Number</th>
<th>Shear Speed (m/s)</th>
<th>Dilatation Speed (m/s)</th>
<th>Mass Density (kg/m³)</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (top layer)</td>
<td>1400</td>
<td>2914</td>
<td>2000</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>1041</td>
<td>2000</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>208</td>
<td>2000</td>
<td>Infinite</td>
</tr>
</tbody>
</table>

Using this pavement profile with top layer, assuming the vehicle as 2009 Toyota Prius with mass 0.005g (1% of speed bump acceleration), and the acoustic radiating wave field in SPL could be expected as Fig. 8-4 with 7cm above ground surface.

Figure 8-4 Acoustic wave field from tire loading (2009 Toyota Prius with mass 0.005g (1% of speed bump acceleration))
The benefits of this plate model is the relative simplification of the pavement/ground as classic plate, the trade-off is that it does not include the pavement profile details or tire footprint area to expect the acoustic response. However, this plate model could still indicate the general or top layer’s property for its acoustic response. With such a forward model, it could be found, with a stiffer pavement, a quieter radiating acoustic response is expected for the same loading input from the tire to pavement.

8.2 Tire Noise in Pavement Debonding Identification using HHT

8.2.1 Theoretical Background

The challenges of acoustic sensing for pavement subsurface

The tire-pavement interaction noise from NCAT data collected in summer 2010 is the source of the acoustic sensing and signal post-processing. The noise data of the tire-pavement interaction consists of all the acoustic information from the environment, such as wind and bird chirp, vehicle structure noise, and engine noise.

As Fig. 8-5 indicated, for the data collected from NCAT, the environmental noise was hypothesized to mainly contain wind noise since other noise sources, such as bird chirps and human voices, could be ignored since the tracks were surrounded by dense forest on both sides. Therefore, the tracks are isolated from the regular urban and highway environment as a silent testing island. Meanwhile, only the VOTERS van was running in the test tracks, so no other vehicle noise sources were involved. Thus, under these experimental conditions, the acoustic data is dominated mainly by wind noise, vehicle structure or engine noise, and surface texture noise. In such case, the pavement subsurface
radiating noise might be minority in the total acoustic signal. It is challenging to extract the pavement subsurface acoustic information from a highly noisy and mixed raw data. In fact, according to the correlation from the acoustic signals to MTD (mean texture depth) and IRI (international roughness index) study, it might be considered that pavement surface texture friction with tires is the most dominant acoustic component with physical background. This noise component could overshadow other acoustic components carrying valuable information, especially the subsurface acoustic radiating response.

The other main challenge is the difficulty in converting the classic surface wave based pavement diagnosis method to a running vehicle based platform. The difficulties could involve the uncertain tire impacts on the pavement, which is different from the point impact source used in SASW or MASW. The other difficulty is the continuous impacts from tires, which might lead to the overlap of radiated signal from pavement subsurface layers in the time domain.

8.2.2 Tire-pavement subsurface acoustic radiating
A model was hypothesized as Fig. 8-6. All the wind noise, vehicle noise, and chassis pavement reflection noise go to the pavement surface together with the tire impacts. In this way, they all affect pavement vibration. However, as long as a directional microphone is used at near surface height, the acoustic signals recorded would be radiated from the pavement, no matter what other sources excite the pavement. The pavement works like a black box and receives exciting sources and then radiates acoustic waves which carry its structure information on the surface.

With such an understanding, the acoustic signal recorded by a directional microphone would mainly collect the sound radiated from the pavement with multiple possible impacting sources. The impacting source could be the vehicle acoustic radiating, the chassis-pavement reflection, or the tires. The exact source does not matter, as long as the pavement structure is treated as acoustic input/output black box. This model might explain why the transfer function from tire axle acceleration to the recorded microphone acoustic pressure failed to match the property for each section of this work. The is because the
output acoustic pressure is not only trigged by the input of tire vertical accelerations, but also by the input of other sources such as the wind, vehicle radiation, and chassis-pavement reflection.

Possible answers to challenges

As discussed above, the challenges relate to the desired pavement subsurface radiating acoustic signals are dominated by the pavement surface texture noise. Meanwhile, according to the analysis of the frequency characteristics of the pavement section sound, the signal is not stationary even within a given pavement section. The pavement structure is also nonlinear due to the viscoelasticity of the pavement material.

Based on these pavement characteristics, in particular the non-stationary and non-linear attributes, as well as highly noisy signal for pavement subsurface diagnosis, the traditional Fourier transfer in frequency domain may not be exact enough to be successful. Additionally, Fourier transform is also not suitable for the non-stationary signals as the pavement black box varies in time or location. The most important requirement is to extract the wanted information from the highly noisy and mixed total signal. To realize this purpose, some signal processing algorithms might be helpful, such as wavelet transform or the HHT (Hilbert-Huang Transform).

Hilbert-Huang Transform and Hilbert Spectrum

The EMD (empirical mode decomposition) and IMF (intrinsic mode function) are the cores of HHT-based analysis. The EMD process is based on the assumption that the original signal could be decomposed into a series of mode functions, which describe the natural physical features of the data. The primary benefit of EMD is the data-adaptive
decomposition is performed without any constraints on the assumption of the function basis, such as sinusoid function for the Fourier Transfer. The function basis is adaptive to the current data. In contrast to other methods, the HHT is adept at analyzing both nonlinear and non-stationary signals. Table 8-2 summarizes the properties of the HHT (Huang et al. 2005).

Table 8-2 Properties of the HHT

<table>
<thead>
<tr>
<th>Basis</th>
<th>Fourier</th>
<th>Wavelet</th>
<th>Hilbert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>a priori</td>
<td>a priori</td>
<td>adaptive</td>
</tr>
<tr>
<td></td>
<td>convolution: global uncertainty</td>
<td>convolution: regional uncertainty</td>
<td>differentiation: local, certainty</td>
</tr>
<tr>
<td>Presentation</td>
<td>energy-frequency</td>
<td>energy-time-frequency</td>
<td>energy-time-frequency</td>
</tr>
<tr>
<td>Nonlinear</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Nonstationary</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Feature</td>
<td>no</td>
<td>discrete: no; continuous: yes</td>
<td>yes</td>
</tr>
<tr>
<td>Extraction</td>
<td>theory complete</td>
<td>theory complete</td>
<td>empirical</td>
</tr>
</tbody>
</table>

The specific EMD and instantaneous time-frequency energy distribution by Hilbert spectrum could be obtained in Huang, N.E and Shen, S.P. (Huang et al. 2005).

**8.2.3 Suspected surface wave identification with the HHT**

Originating from the concept of the pavement surface wave based diagnosis; the surface wave could be affected by a running vehicle tire exciting style. However, the surface wave excited by a continuously vehicle running could be different from the discrete impact method which is used in pavement subsurface inversion methods, such as SASW.
In Fig. 8-7, a typical impact-echo SASW test setting was shown, where S1 and S2 were the impact sources, while the R1 and R2 were the receivers. The time domain signal indicated the surface wave reflected in the plate with the thin void-like debonding in the pavement.

![Impact-echo with HHT to extract surface wave](image)

Figure 8-7 Impact-echo with HHT to extract surface wave

As learned from the impact-echo with HHT (Lin et al. 2009), some criteria could be established and expanded to the continuous vehicle tire running impact to identify the surface wave signal. These hypothesized criteria were summarized in Table 8-3.

<table>
<thead>
<tr>
<th>Criteria for surface wave characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat and wide range frequency character</td>
</tr>
<tr>
<td>No apparent peaks in frequency span</td>
</tr>
<tr>
<td>Relative high energy ratio</td>
</tr>
</tbody>
</table>

Table 8-3 Criteria for surface wave characteristics

It could be explained as follows. Firstly, the surface wave for pavement inversion is broadband to cover from the shallow pavement subsurface to the deeper subsurface layers. Therefore, the frequency spectrum should be wide and flat in the frequency band. Secondly, there should be no apparent peak in the frequency spectrum since the peak in frequency might indicate a resonance of the structural vibration from the vehicle. Finally,
a surface wave might carry more energy than other body waves such as the P-wave or S-wave. Due to the unknown environmental noise energy distribution, the decomposed mode involving surface waves might be a local energy maximum point. However, these criteria are more trusted in discrete impact testing. Future study would be needed for a deeper understanding.

Based on such supposed criteria, the suspected surface wave was extracted with the process flow chart as Fig. 8-8.

Figure 8-8 HHT based surface wave identification from vehicle running impact

As Fig. 8-8 implied, the HHT automatically did the band-pass sifting in a more physically meaningful way. And due to its spline fitting mean value subtraction, the DC (direct current component) could be removed simultaneously.

8.2.4. Signal Processing Results and Discussion with HHT
The proposed HHT based method was applied to the tire-pavement noise records from NCAT (National Center for Asphalt Technology) test sections with known artificially built subsurface defects.

The van ran with three speeds: 20mph, 35mph, and 50mph. Currently, without considering the high speed scanning requirements, the 20mph speed was decided as prior speed selection since the special test sections are relatively short (25ft in length). So with a lower van speed, a greater amount of data could be analyzed from the test sections.

Figure 8-9 showed the typical decomposition modes of the total acoustic signals. The top plot indicated the raw acoustic signal to be analyzed. The left bottom plot showed the decomposed intrinsic mode functions from mode 5 to mode 8. Actually, more results of the decomposed intrinsic mode functions could be collected and placed here, but to save the space in the report, the decomposed intrinsic mode functions without apparent physical
meaning were not shown. Additionally, the right bottom plot showed the frequency spectrum of the each mode corresponding to the bottom left plot. According to the bottom right plot, band-pass filtering sifting from high broader frequency span to low narrower frequency span could be observed. Specifically, the frequency spectrum of mode 5 was 0Hz – 4kHz range with the strong energy band 0.2kHz to 2kHz. This strong energy band matched the penetration depth as 0.12 ~ 1.2m of surface wave with the assumption of typical averaged phase velocity of surface wave as 800m/s. This surface wave penetration depth is well suited for shallow pavement subsurface sensing. However, if more shallow depth is critical, a higher frequency strong energy band is needed. The frequency spectrum of mode 7 had an apparent peak around 100Hz, which coincided with the sound pressure spectrum with Welch's averaged FFT. Similarly, the frequency spectrum of mode 8 had a peak around 200Hz coinciding with the Welch's averaged FFT spectrum peak as Fig. 8-10.

Figure 8-10 Sound pressure spectrum

These two peaks are always present for different speeds and different sections and are assumed to be vehicle engine or structural resonances. Therefore, mode 7 and 8 were intrinsic modes mainly consisting of vehicle engine or structural noise, respectively.
However, since the spectrum of mode 7 and 8 were not only two peaks alone, there still existed some signals, which were neither engine nor structural noise. However, the plot was drawn in dB manner, so the other signals in mode 7 and 8 could be roughly ignored since their energies were minor in the frequency band. The frequency spectrum of mode 6 had similar shape with mode 5, but with a lower and narrower frequency span. Mode 6 failed to be extracted a suspected surface wave due to two main considerations. One was that its frequency band was not as wide or flat as mode 6 to supply with an ideal penetration depth of surface wave. Its penetration depth was from 0.3m to 1.2m, which could not cover the shallow depth adequately. The other consideration was mode 5 owned larger energy proportion than mode 6, as shown in Fig. 8-11.

![Normalized energy in each mode](image)

**Figure 8-11** Normalized energy in each mode

Based on these assumptions and analysis, the most attention was given to mode 5. An instantaneous frequency-time distribution was processed for mode 5. At the beginning, the frequency-time distribution seemed random. However, when the distribution was constrained to below 100Hz, it seemed some phenomena was present. The frequency value dropped dramatically, down to near 0Hz. Since the points were sampled very quickly in
the time domain, the frequency-time distribution curve looked like vertical straight line, as shown in Fig. 8-12.

![Figure 8-12 Frequency-time distribution within 100Hz](image)

According to Fig. 8-12, much of the frequency-time distribution took the form of vertical straights lines that corresponded to shallow depth subsurface changes. However, some locations where short vertical straight lines were indicated failed to match subsurface changes. These unmatched short lines and points were assumed to be due to noise in the data. The noise might affect the accuracy of locating the subsurface situation change point. A possible reasons for the uncertain short lines and noise points might be that the mode 5 surface wave signal was noisy, which resulted in some information of the surface wave signal was being lost. This means that some other unwanted noise was present in mode 5, while some surface wave components were might be removed in other decomposed modes, which could also consist of some surface wave components.

Thus, more efforts should be made to improve the extraction accuracy of the surface wave signal from the noisy raw data. Also, some confidence evaluation should be established to judge the effects of the mode separation and suspected surface wave extraction.
A more confidence method to diagnose subsurface defects was tried through use of the mode energy proportion distribution characteristics, as shown in Figure 8-13. There were always 18-20 modes decomposed from raw data. The max energy proportion peak happened at modes 13-17, while the local sub-max peak happened at modes 4-6. Thus, the principle idea of this method was to compare the normalized mode energy proportion distribution of healthy pavement to pavement with subsurface defects.

Figure 8-13 Comparison of normalized mode energy proportion

Figure 8-13 indicated the pavement with subsurface debonding had a lower energy distribution proportion in the suspected surface wave modes bands. It could be explained physically that the pavement with subsurface defects transmits less surface wave energy. In Fig. 8-13, the distribution curves in the low mode index band of the healthy and subsurface debonding pavements failed to converge like in the high mode index band.

According to Fig. 8-14, for all three runs on the special test sections, the pavement with debonding has lower energy proportion in the low mode index (which mapped to the high frequency band), compared with healthy pavement with the identical surface. This indicates more energy transmitted to the lower frequencies for the pavement with debonding.
8.2.5. Conclusions and Future Work

Analysis of acoustic signals measured by microphones mounted underneath a moving van has indicated that the signal is nonstationary, but carries information about the pavement subsurface. An HHT-based method has been shown here to identify intrinsic modes that might be useful in identifying subsurface defects. The surface wave amplitude frequency-time distribution indicates changes in subsurface material properties. Analysis of the normalized mode energy proportion distribution curve might differentiate between pavement with subsurface defects and healthy pavement. Other approaches, such as analysis of moving window transfer functions (from tire axle acceleration to acoustic pressure), moving window sound energy of mode, and moving window coherence did not improve the HHT performance. The HHT-based method was time consuming due to the iterative mode separation and the confidence of the suspected surface wave extraction needs to be improved and verified. Investigation of the normalized mode energy proportion distribution curve method indicate the potential to identify the surface wave band.

Figure 8-14 Normalized mode energy proportion distributions for three runs (Blue: healthy pavement; Green: pavement with debonding)
9 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

9.1 Conclusions

This dissertation has developed a systematic methodology of mobile acoustic subsurface sensing for roadways. The developed system allows for efficient and effective mobile profiling of a road’s subsurface condition through non-contact acoustic signals with microphone measurement.

The dissertation has presented a full scale high resolution air-coupled pavement finite element (FE) model to verify the feasibility of non-contact acoustic sensing of radiating surface waves. According to the FEA on typical pavement, the radiating surface wave which is radiated from the ground surface wave is found to perform pretty closed to a plane wave; it brings the same information as a ground surface wave. Meanwhile, the energy of a radiating surface wave is adequate for the acoustic pressure measured with microphone. The phase velocity difference between the radiating surface wave and the direct sound wave as unwanted noise is large enough to separate. It also found that surface waves perform more like Lamb waves when there is open de-bonding between layers. More energy is trapped within the open de-bonded layer. In this case, resonances from 200Hz to 1400Hz could be found with the radiating acoustic surface wave.

A numerical model based on a stiffness matrix and particle acoustic radiation principles was also developed to predict the radiating acoustic surface wave field above pavement. Compared with the FEM, the numerical model is more efficient for computation. FEM
requires hours or days to perform calculations, but this numerical model takes only minutes. The numerical model allows a fast parametric study as virtual field test for the interested factors such as impulse magnitude and frequency feature, impactor contact area, ground profile information and virtual measurement location.

Based on studies of radiating acoustic surface waves, the dispersion curve can be found using microphone sensing, which is similar to ground pasted accelerometer or geophone sensing. A wave number fitting method with consideration of the imaginary wave number for the damp or decay information of surface waves was proposed to provide accurate dispersion curves. This method was more robust and accurate for acoustic sensing compared to Spectral Analysis of Surface Waves (SASW). With accurate dispersion information, the inversion analysis is used to estimate the subsurface profile. Two inversion algorithms were developed in this research. A fast inversion algorithm based on the in-situ particle displacement distribution of fundament wave modes was originally proposed. Compared to current inversion methods such as SASW, Artificial Neural Network (ANN), Fast Simulated Annealing (FSA), Generic Algorithm (GA), the fast inversion algorithm owns the advantage of highly efficient back-calculation. The algorithm was validated through an analytical stiffness matrix based forward modeling, and other published research. Based on the in-situ particle displacement distribution of fundament wave modes, this algorithm would perform limitation for considerably stiff top layer. In this case, the fundament surface wave would jump as Lamb waves. To overcome this limitation, a Lamb wave based inversion algorithm was proposed. Through tracing the measured dominant dispersion curve and fitting it with a Lamb wave A0 mode, an accurate inversion of the
profile with stiff top layer can be realized. This algorithm was also validated with analytical
stiffness matrix based forward modeling and field tests.

To implement the non-contact, efficient subsurface sensing by microphone, an integrated
platform has been developed as Mobile Acoustic Subsurface Sensing (MASS) prototype.
This prototype embeds the software of developed algorithms onto a three-wheeled cart with
an automatic electromagnetic impulse hammer, DAQ system, distance trigger and
directional microphones. A mechanical sound enclosure was designed to block
environmental noises and collaborates with the directional microphone to pick up the
acoustic radiating surface waves. The digital acoustic signal filters were also developed to
identify and verify the quality of radiating surface waves automatically. With both
mechanical sound enclosure and digital signal filters, the signal to noise ratio (SNR) for
field testing has been considerably improved. Up to 20dB level SNR could be reached
during field testing. The MASS DAQ consists of a signal conditioner, a DAQ motherboard,
a Single Board Computer (SBC), DC power converter, and solid state hard drive. A High-
performance Intel Core 2 Duo processor was used with the Operating System QNX. The
data acquisition system allows a high sampling rate (up to 200 kHz) to pick up adequate
signals for the passing transient waves. The capability of the MASS prototype was
validated on asphalt pavement, concrete slab and concrete bridge deck field tests. Despite
these achievements, further efforts are necessary. A better impact source would be
suggested to offer more stable and sharp excitation to supply high coherence signals for
desired frequency range. A better design for the de-noise mechanism on the mobile
platform is also recommended.
Additionally, studies on the tire excited elastodynamic response sensing on pavement for subsurface characterization were also discussed with the aim of implementing the subsurface sensing more efficiently on a vehicle in natural traffic conditions. An elastic plate based pavement model was proposed to estimate the tire loading effects on the ground. A HHT (Hilbert–Huang transform) based method was discussed to identify the debonding underneath the pavement with identical surface texture through the NCAT test.

To summarize, the mobile acoustic subsurface sensing methodology developed in this dissertation provides an efficient and effective non-contact assessing pattern for the pavement monitoring. It contributes to the urgent demand for national transportation health monitoring in the United States.

9.2 Recommendations for Future Study

The dissertation summarized and concluded the efforts and achievements done for an efficient mobile subsurface sensing of roads by using radiating acoustic surface waves through microphones. The challenges come together with acoustic signals sensing. For the mobile acoustic subsurface sensing to be better implemented, several areas require further study.

1. The impact source of MASS platform would need improvement with better shock performance to offer more stable and sharp impulse to cover high coherence for the whole interested frequency range. The alternative improvements could be gas-pressured or hydraulic-pressured impact sources with closed-loop control.
2. The de-noising for acoustic signal sensing may need further improvement. For example, an overall mechanic sound hood design could be helpful to isolate the near ground space of sensing area from environmental noise in field test. Some advanced filters for acoustic transmitting domain might be learned for the radiating surface waves.

3. The inversion of surface waves and radiating surface waves for subsurface profiling of roads encounters the difficulties for gaining both thickness and stiffness for pavement layers as the mechanical properties. A complementary radiating surface wave measurement and air-coupled GPR measurement would help each other for more accurate testing. Firstly, the layer boundaries could be determined from the GPR data. This information is used as starting values in the acoustic inversion determining the mechanical properties.

4. A mobile testing through regular vehicle tire excited elastic wave sensing would need further study for the benefits of traffic speed testing. The alternative solutions might be using moving window to observe the transfer function from the tire axle acceleration to the dynamic pressure inside the tire measured by DTPS (Dynamic Tire Pressure Sensor). The tire axle acceleration would be assumed as impulse input to the road, the DTPS reading could be considered as the contact response from the road. Further field testing where variant subsurface conditions with the identical surface texture would help to validate and accomplish this proposal.

5. For above proposal, the transfer function from the tire axle acceleration to DTPS reading might be correlated to the general mobility of the roads. Further study
may be attractive to build up a relationship between the measured TF (transfer function) and the general mobility which presents the general stiffness of roads by the ratio of response velocity over the impulse force.
REFERENCES

Al-Hunaidi, M.O., Difficulties with phase spectrum unwrapping in spectral analysis of surface waves nondestructive testing of pavements, Canadian Geotechnical Journal, 506-511, 1992

Ali Zomorodian, S.M. and Hunaidi, O., Inversion of SASW dispersion curves based on maximum flexibility coefficients in the wave number domain, Soil Dynamics and Earthquake Engineering, v 26, n 8, p 735-752, August 2006

ASCE, 2013 Report Card for America’s Infrastructure Road

ASCE, 2013 Report Card for America’s Infrastructure Bridge


Chen, L., Zhu, J., Yan, X. and Song, C., On arrangement of source and receivers in SASW testing, Soil Dynamics and Earthquake Engineering, v 24, n 5, p 389-396, July 2004

COMSOL Multiphysics 3.5a, Acoustic Module Users’ Guide, 2009
(http://www.comsol.com/products/acoustics/)

Dunkin, J. W., Computation of modal solutions in layered, elastic media at high frequencies, Bulletin of the Seismological Society of America, 55, 2, 335-358, 1965


Ke, W., Castaings, M. and Bacon, C., 3D finite element simulations of an air-coupled ultrasonic NDT system, NDT&E International 42 524-533, 2009


Moore, W., An instrument for detecting delamination in concrete bridge decks, Research Report Number 130-4, A Study of Reinforced Concrete Bridge Deck Deterioration: Diagnosis, Treatment and Repair, Research Study Number 2-18-68-130, 1973

National Center for Asphalt Technology Test Track
(http://www.eng.auburn.edu/research/centers/ncat/facilities/test-track.html)


Park, C.B., Imaging dispersion of passive surface waves with active scheme: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2008), Philadelphia, April 6-10 2008


Rosenblad, B.L. and Bertel, J.D., Potential phase unwrapping errors associated with SASW measurements at soft-over-stiff sites, Geotechnical Testing Journal, v 31, n 5, p 9 pp., 1 Sept. 2008


Thomson, W. T., Transmission of elastic waves through a stratified soil media, MIT research report R 81-2, Order no. 689. Cambridge, MA, Department of Civil Engineering, MIT, 1950


Waas, G., Earth vibration effects and abatement for military facilities, Technical Report S-71-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss, 1972

Xia, J., Miller, R. D., and Park, C. B., Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves, Geophysics, 64, 691-700, 1999

