1 Introduction

> Creatively dreaming Nature dreamed here and there the same dream: if there could be a thought of imitation, then surely it was reciprocal.
>
> Thomas Mann, *Doctor Faustus*

1.1 Introduction

Site specific near-surface earth conditions exert considerable control over the response of foundations and structures to earthquakes and dynamic motions. To adequately design structures to minimize earthquake hazards, the shear modulus and shear damping ratio of the underlying soil layers must be determined. Once the layered material properties have been determined, a site response analysis can be conducted to determine the optimum engineering design.

Soils exhibit complex material response characteristics, depending on factors including strain level, state of effective stress, and loading history. In general, soils are non-linear, inelastic materials, but at very small strain levels, the material response can be assumed linear viscoelastic. The primary dynamic material properties, shear modulus and shear damping ratio, can be determined from several different types of tests, each offering different advantages and disadvantages. The shear modulus controls the velocity of shear wave propagation, and the shear damping ratio controls energy dissipation.

Soil material properties can be measured in the laboratory, but lab testing suffers from several impediments, including disturbance during sampling and transportation to the lab. To overcome some of the difficulties associated with lab testing, several in situ tests have been developed to determine the low strain dynamic properties of soils.

Geotechnical in situ seismic testing relies upon dynamic sources created from either an impulsive or harmonic source. This dissertation is devoted to the determination of dynamic properties of soil through engineering analysis of seismic surface waves. Spectral analysis of surface waves (SASW) tests determine the Rayleigh surface wave dispersion and attenuation curves, which equal phase velocity and material attenuation as a function of frequency, respectively. Engineering analysis of seismic surface wave tests can be classified into two categories, based on the type of source utilized. *Active* surface wave tests use an impulsive or harmonic point source to create a seismic surface wavefield. *Passive* sources consist of ambient energy propagating along the surface of the earth, such as traffic, cultural noise and microtremors. The different types of sources and advantages and disadvantages of each are discussed in Chapter 5.

After the dispersion and attenuation curves have been determined for a particular site, an inversion algorithm determines the layered soil shear modulus and damping properties that most closely match the experimental measurements. Any error or bias in the estimated dispersion curve directly impacts the ability of the inversion algorithm to determine the correct layered soil profile. Although the inversion problem has received a great deal of attention in the past, the determination of the dispersion curve from active surface wave point sources has not changed significantly since the introduction of SASW testing into the geotechnical field.

The neglect of the experimental dispersion curve estimation procedure in the geotechnical field probably stems from the ease with which a dispersion curve can be estimated, even though it may be incorrect, while the inverse problem requires a great deal more effort. The dispersion curve is easy to estimate through traditional analysis methods, but the common procedures used in geotechnical engineering to analyze seismic surface wave experimental data suffer from several limitations. In fact, as Chapter 6 will show, the traditional methods currently used to analyze active surface wave data will *never* yield the correct answer, even in the most simplistic and idealistic circumstances, e.g. a single wave measured in zero noise, due to using the incorrect physical model.

The following sections will provide the framework for the rest of the dissertation. First, the importance of soil material properties to site response will briefly be presented, providing the underlying motivation for soil material property determination. A general overview of the major problems associated with the current approach to geotechnical engineering analysis of seismic Rayleigh surface waves will be discussed. Then, an outline of the solution methodology presented in this dissertation is given. Since correct understanding and usage of terminology plays an important role in clarifying scientific

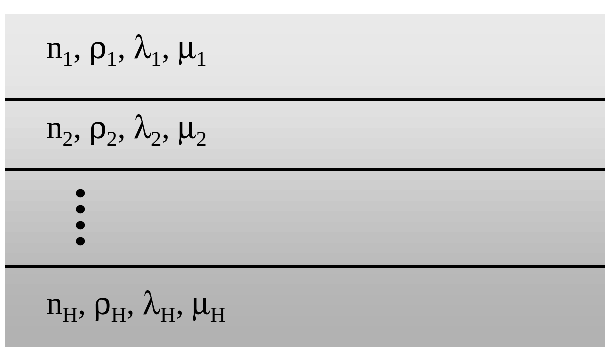

Figure 1.1 Ideal Layered Soil Profile

concepts, a section on terminology will introduce and attempt to unambiguously define several of the concepts used throughout the dissertation. Last, an overview of the research objectives and contents of the dissertation are given.

1.2 Importance of Dynamic Soil Material Properties

The material properties of layered or vertically heterogeneous soil profiles strongly affect the magnitude of ground surface shaking due to energy propagating along the surface of the earth or emanating from a buried source. Figure 1.1 shows the ideal, stacked layer model assumed in most geotechnical surface wave analyses. The model consists of n_i homogeneous soil layers (for i = 1 to number of soil layers) above a homogeneous halfspace, n_H. For each layer, the density ρ and the Lame parameters, λ and μ, specify the material response to dynamic excitation.

Figure 1.2 shows the influence of the initial tangent shear modulus (G_{max}) on a reference input motion applied to the base of a 30 meter homogeneous soil deposit overlying bedrock, computed using SHAKE91 (Lai, 1998). Different G_{max} values yield significantly different spectral responses. Knowing the spectral response characteristics of a soil profile allows engineers to design foundations and structures to avoid the natural frequencies of the system. The difference in spectral response due to variation of initial shear damping ratio (D_{Smin}) is also significant. For a more detailed introduction to site response analysis, see Kramer (1996).

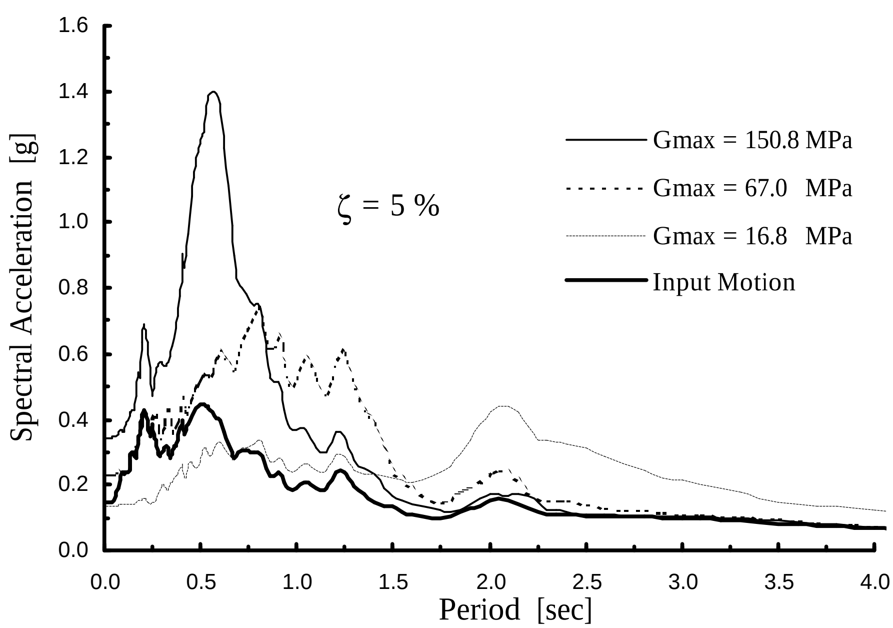

Figure 1.2 Geotechnical Site Response Analysis as a Function of Maximum Shear Modulus G_{max} (From Lai, 1998)

1.3 Current Geotechnical Engineering Seismic Surface Wave Analysis

The current active seismic surface wave analysis procedures used in geotechnical engineering suffer from several limitations, discussed fully in Chapter 2. The problems can be classified into the following two general categories:

1.) Use of the incorrect physical model,

2.) Inadequate signal processing methods.

The use of the incorrect physical model for cylindrically spreading wavefields from a point source has led to unfavorable developments in the analysis of both phase velocity and attenuation. Chapters 6 and 7 will thoroughly discuss the problems associated with the incorrect physical model, proceeding to optimum solutions based on the correct model. The traditional surface wave analysis methods suffer from poor spectral characteristics and simplistic signal processing. The advanced signal processing methods introduced in Chapters 3 and 4 yield significant improvements in the solutions obtained from seismic surface wave analysis. Advanced signal and spatial array processing will solve the most acute problems associated with traditional geotechnical surface wave analysis. In addition, advanced signal processing methods and synthetic linear arrays will allow significant extensions of the results obtained from common SASW test setups utilizing only two sensors, as discussed in Chapters 6 and 7.

1.4 General Seismic Surface Wave Problem and Solution Methodology

The temporal natural frequency estimation problem provides the consummate analogue to the spatial spectral estimation problem. The left panel of Figure 1.3 shows a typical single degree-of-freedom spectral response, with a single peak at the natural temporal frequency of the system. The general characteristics of the spectral response graph are identical for both mechanical single degree-of-freedom systems and RLC circuits. Mechanical response is described by stiffness, inertia, and damping, while RLC circuits are described by resistance, inductance, and capacitance. The one-dimensional natural frequency represents an eigenvalue problem, and in more complex problems, multiple modes of propagation exist.

In vertically heterogeneous soil profiles, the spatial spectral response exhibits multiple modes of propagation. In ideal layered profiles, multiple modes arise due to the interaction of the energy with layer interfaces and the surface of the earth. In profiles with gradually changing material properties with depth, curved ray paths lead to multiple modes of propagation. The right panel of Figure 1.3 shows the general characteristics of the expected spectral response for a vertically heterogeneous soil profile. The peaks in the wavenumber, or "spatial" frequency, spectrum occur at the “natural” spatial characteristics of the soil profile, depending on site-specific material properties and layering characteristics.

Estimation of the natural wavenumbers, or equivalently, the multimodal dispersion relation, of a layered soil profile represents the overriding problem of all analyses of experimentally measured seismic surface waves. The experimental determination of the dominant wavenumbers can be viewed as an experimental rooting of the Rayleigh secular equation. The natural wavenumbers directly yield phase velocity estimates, and the ability to isolate individual modes of propagation vastly improves attenuation estimates. The natural wavenumbers and attenuation coefficients are then used in an inversion process to determine the dynamic material properties of the layered system. A general overview of the solution methodology will help guide the reader through later chapters detailing the solution implementation.

The engineer desires knowledge of the dynamic properties of the layered soil system, but in surface wave testing, a gap exists between the parameters that can be estimated from experimental data and the actual properties necessary for engineering design. To determine the best estimate of the dynamic soil properties, the optimum estimate of the dominant wavenumbers must first be extracted from experimental data. The extraction of a single wavenumber, and knowledge of which wavenumber has been isolated, represents a difficult problem in traditional engineering analysis of seismic surface waves.

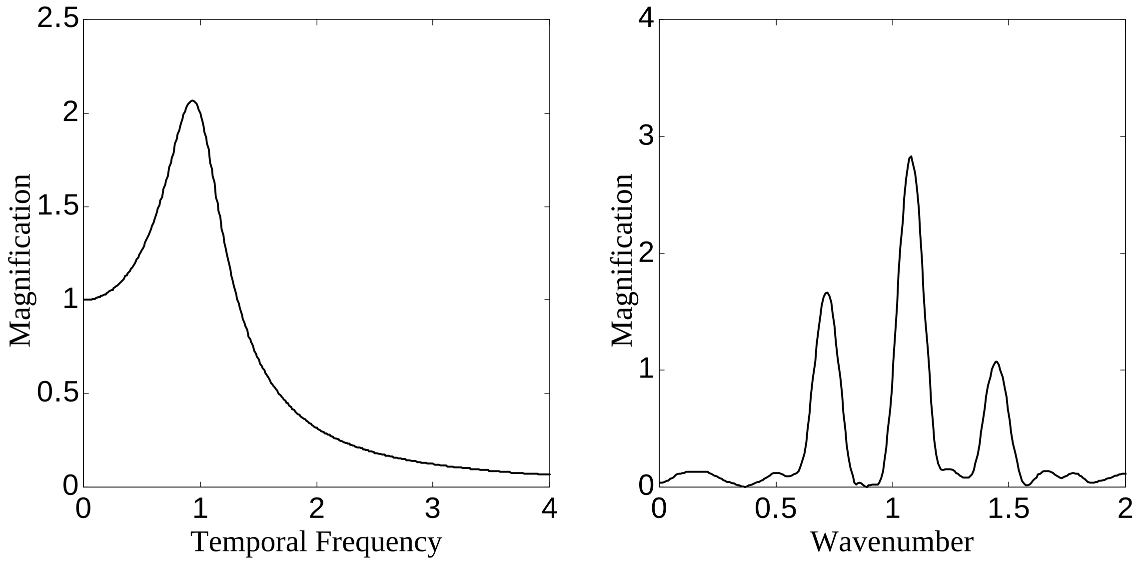

Figure 1.3 Single Degree-of-Freedom (SDOF) and Multiple Degree-of-Freedom (MDOF) Spectral Response Characteristics. The left panel shows a typical "resonance" phenomena for a single degree-of-freedom system, which is commonly encountered in circuit and material property analysis. The expected multiple degree-of-freedom spatial response for a vertically heterogeneous soil profile (right panel) displays multiple resonance peaks.

To determine a single wavenumber component, an *optimum* spatial filter, with adequate resolution and sidelobe control to sift out a single spectral component, must be designed. In signal processing and filter design, the term optimum encompasses many different solution techniques, and the optimum solution for a given problem depends on the underlying characteristics of the system being measured. Figure 1.4 shows the conceptual flow of the problem solving methodology involved in the analysis of experimental seismic surface wave measurements. The top of the figure shows the desired information to be obtained from experimental measurements. The dominant wavenumber components will correspond to the peaks in a frequency-wavenumber (f-**k**) power spectrum, and obtaining a

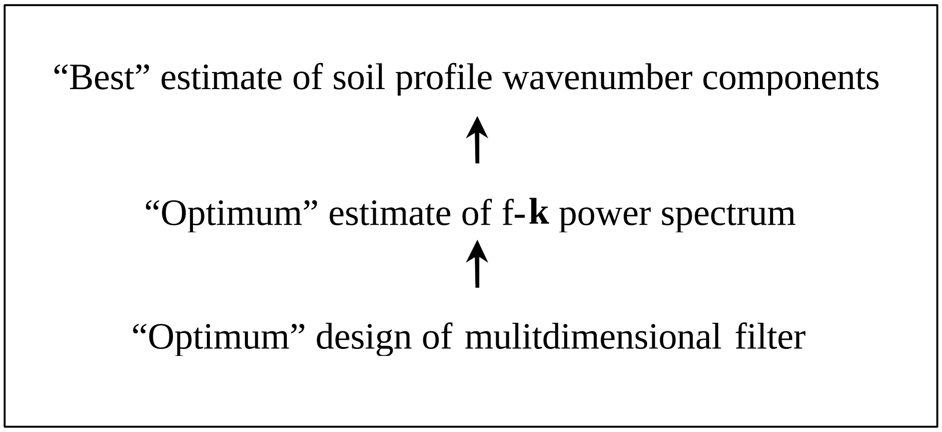

Figure 1.4 Seismic Surface Wave Wavenumber Estimation Methodology

good estimate of the power spectrum requires designing an optimum multidimensional filter. Much of this dissertation is dedicated to determining the characteristics and the design of optimum multidimensional filters.

Optimum spatial signal processing depends on a combination of the array design and the choice of signal processing algorithms. First, the array geometry controls how the spatial wavefield is sampled and determines the physical array spectral properties. Analogous to the temporal domain, in which sampling frequency and total length of data exert limits on the ability to estimate a spectrum, the spatial sampling rate and total aperture length also exert limits on the ability to estimate spatial spectral properties. In geotechnical surface wave analysis, the engineer has complete control over the design and deployment of spatial arrays. In some engineering cases, such as radar dishes, the ability to sample a spatial wavefield is limited based on the directional characteristics of the receiver. Second, the choice, efficiency, and design of signal processing algorithms, for example window choice, affect the ability to obtain optimum spectral estimates.

In spatial array processing terminology, the combination of the physical array design and signal processing algorithm allows the engineer to *focus* on particular directions and sources of propagating energy. Figure 1.5 shows a schematic of the primary spatial array design problem. In addition to the array geometry and algorithm choice, sensor calibration weights play an important role in signal processing. The introduction of sensor calibrations is easily achieved, and will be discussed in Chapter 4.

1.5 Terminology

Explicitly defining several terms encountered throughout the dissertation will ease consideration of closely related, and sometimes seemingly ambiguous, concepts. In many cases, commonly used words, such as apparent and conventional, are adapted for specific

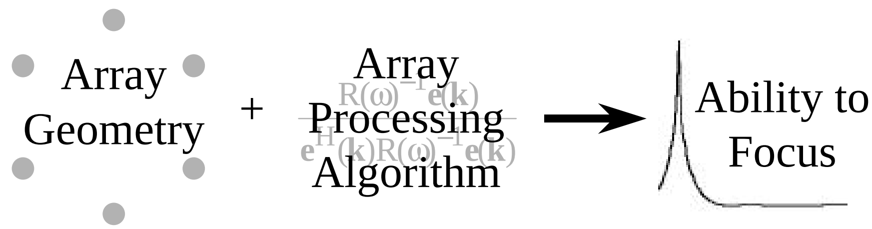

Figure 1.5 Focusing a Spatial Array. The array geometry plus the array processing algorithm control the ability to focus an array on a particular direction or wavenumber.

scientific and engineering meanings. Although most terms are defined when they appear, the present section will cover a few terms that are either general to the entire thesis or discuss varying terminology found in different disciplines.

The most common geotechnical surface wave phase velocity estimators, the two-point cross power and transfer function methods, will be referred to as *traditional two-point* or *traditional* estimators. In electrical engineering, the commonly used spatial array processing algorithms have already been categorized, and maintaining the same electrical engineering terminology allows the traditional geotechnical estimators to be discussed without ambiguity. The earliest spatial array processing estimators, the time domain and frequency domain beamformers, are called *conventional* estimation methods. Estimation methods that change depending on observed signal and noise characteristics, including methods such as minimum variance distortionless look, MUSIC, and linear prediction, are called *adaptive* estimators. Therefore, the three categories of estimators discussed in this thesis include *traditional*, *conventional*, and *adaptive* methods.

A major consideration in seismic surface wave analysis deals with determination and mitigation of near-field effects. Near-field effects have been the *deus ex machina* of problems encountered in the analysis of geotechnical active source seismic surface wave data. Since the term near-field has been used often in geotechnical surface wave analysis, the term demands an unambiguous definition. The near-field effects due to modeling a cylindrical wavefield with a plane wave while not in the far-field, i.e. the far-field assumption is not valid, will be called *model incompatibility effects*. The near-field effects due to body wave reflections at an interface that <u>do not contribute</u> to additional Rayleigh surface wave modes will be called *near-field body wave effects*. The inability of traditional estimators to distinguish between multiple surface wave modes, i.e. body wave superposition <u>contributing</u> to additional surface wave modes, will be called *far-field body wave interference*. The terms will be clarified more completely throughout the dissertation, but engineers familiar with active source seismic surface wave analysis should have a general intuition regarding the meaning of the terms as proposed. Previous studies combine the three separate physical entities into a single effect, called near-field and body wave interference effects, and then base recommended test procedures and filtering criteria on the combination of all three interference effects.

The term attenuation encompasses several energy dissipation mechanisms, which will be discussed in Chapter 2. The term geometric attenuation is used to describe the spreading of energy over a larger area as it propagates, for example, a spherically spreading wave. The choice of terminology is unfortunate, since no energy is being attenuated, and in this dissertation, the term *geometric spreading* will be used exclusively. The proper modeling of geometric spreading is intimately related to material attenuation estimates, and removing any ambiguity between the two will aid in the analysis described in Chapter 6.

The fundamental surface wave mode in a homogeneous half-space represents a different physical phenomenon than additional modes created in layered systems, as discussed in Chapter 6. In the common stretched-string problem used to introduce wave propagation, the meaning of fundamental mode and higher modes is unambiguous. In traditional geotechnical analysis, the lowest velocity mode is assumed to correspond to the fundamental mode and all other modes are considered higher modes. A problem in terminology arises when comparing the physical mechanism that creates the fundamental mode and the lowest velocity mode in a layered medium, which may arise due to wave guide or layer interface effects. If the lowest velocity mode is due to reflection of energy at layer interfaces, the mode represents something different than the homogenous half-space fundamental mode. In addition, due to the scale effects of different wavelengths compared to layer heights, the lowest velocity mode may change as a function of frequency, i.e. two modes may cross at certain frequencies. To avoid ambiguity in the use of fundamental and higher modes, the dissertation uses the term *dominant mode* to refer to the mode containing the greatest energy and *additional modes* to refer to any additional modes isolated, regardless of relative phase velocities.

1.6 Research Objectives

Four primary areas deserving attention were identified at the beginning and during the evolution of this research. Although passive surface wave analysis served as the original impetus for the research, solutions to the passive problems could not have been obtained without considering the more tractable one-dimensional active surface wave problem.

1.6.1 Reconsider Common Active Surface Wave Test Limitations

Several aspects of traditional surface wave analysis and the explanations for commonly encountered impediments are reconsidered. Near-field effects, the inability to handle multiple modes, and the ad-hoc nature of traditional testing recommendations stand out as areas desiring simpler and more appealing constructions. The growing complexity of the phase velocity and attenuation models, with only marginal gains in estimation and analysis abilities, also stands out as an area deserving reconsideration. The common limitations and problems associated with active surface wave testing are identified and systematically isolated and analyzed, yielding more robust and physically correct physical models.

1.6.2 Extend Active Surface Wave Analysis Abilities

Empowered with advanced signal and spatial array processing methods, considerable additional information can be extracted from the two-sensor active surface wave test. The traditional limitations are removed, and the capabilities of the two-sensor test are extended with synthetic linear arrays, including the ability to estimate multiple mode phase velocities and attenuation coefficients, and the ability to measure longer wavelengths.

1.6.3 Place Spatial Array Processing on *Terra Firma* Within Geotechnical Field

The theory of spatial array processing, which has received little attention while proceeding to experimental results in the geotechnical field, demands thorough coverage. A full arsenal of spatial array processing theory enables a much simpler and satisfying analysis of both active and passive seismic surface wavefields, and the theory underlying spatial array spectral operators aids in spatial array and algorithm choice.

1.6.4 Extend Passive Surface Wave Estimation Capabilities

Passive surface waves offer several advantages over traditional active surface wave attenuation estimates, yet a passive attenuation coefficient has not been estimated previously. The longer wavelengths *vis a vis* active surface waves and the far-field, plane wave nature of many passive surface wave sources suit them admirably for attenuation estimation (Glenn J. Rix, personal communication). On the other hand, the statistical nature of passive energy sources, such as possible nonstationarity in time and space, introduce possible complications.

1.7 Dissertation Overview

The dissertation is organized into introductory, theoretical, and experimental chapters. Chapter 2 introduces and motivates the seismic surface wave analysis problem. Chapters 3 to 5 introduce signal processing theory and practical testing considerations, and then the experimental results from two sites in Atlanta, GA are presented in Chapters 6 to 8.

The dissertation begins with a review of the traditional geotechnical engineering surface wave analysis techniques. Chapter 2 introduces the primary objectives of engineering analysis of seismic surface waves, the traditional parameter estimators, and critically examines the limitations and primary areas requiring further investigation. In addition, to yield a more complete picture of the goals of near-surface site engineering property investigation, the inverse problem of estimating shear wave velocity and material damping profiles are briefly discussed.

The theories of signal and spatial array processing are covered in Chapters 3 and 4. Chapter 3 covers the one-dimensional, temporal signal processing problem. Chapter 4 discusses the theory of multidimensional, spatial array processing and includes synthetic examples of ideal wavefields and algorithm performance. The two chapters are complementary and attempt to emphasize the parallels between the one-dimensional and multidimensional problems.

Some of the practical aspects of array measurements are discussed in Chapter 5. The equipment used during measurements and considerations regarding source characteristics are discussed. The chapter ends with a comparison of several common array geometries and their spectral characteristics, including a few arrays previously used in the geotechnical field.

Chapters 6 and 7 contain the experimental results of an active surface wave test. Chapter 6 begins with a thorough discussion of the major impediments to estimating active surface wave phase velocities. Experimental data is then analyzed with the methods presented in Chapter 4. Optimum cylindrical beamformers are then introduced and compared to the plane wave estimators. The estimation methods, including the traditional two-point methods, will be discussed in detail regarding the effects of the model incompatibility.

Chapter 7 reassesses the capabilities of the traditional attenuation estimators, and introduces the optimum, cylindrical wavefield physical model. The model completely accounts for geometric spreading of energy, and with the aid of multiple mode wavenumber estimates from Chapter 6, yields multiple mode attenuation coefficients.

Chapter 8 discusses the analysis of experimentally measured passive surface waves. First, the passive surface wave model is discussed, especially regarding the differences between the active cylindrical wave and passive plane wave models. Then, the passive source dispersion curve is estimated, and passive surface wave material attenuation coefficient estimates are introduced. Last, Chapter 9 discusses the major results and conclusions of this research, and gives recommendations for further research.