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Potential Replacement of the US Navy's Rapid Penetration Test with the Method of Multichannel Analysis of Surface Waves

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Potential Replacement of the US Navy’s Rapid Penetration Test with the Method of Multichannel Analysis of Surface Waves

by

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This Thesis titled "*Potential Replacement of the US Navy's Rapid Penetration Test with the Method of Multichannel Analysis of Surface Waves*" by William Talmadge Fletcher is approved:

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Dedication

This work is dedicated to my wife Sarah and my children, Olive and Hiroshi. They are the driving force in all my personal and professional endeavors and provide me with the happiness, peace, and comfort to continue striving for my best, each and every day.

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I would like to thank my advisor, Dr. Bill Dally, for all the support, knowledge, insight, and mentorship he has provided me over the course of my studies. His combination of theoretical expertise and experience in the practical application of theory to the field have led me to appreciate the pursuit of root causes but to also have the ability to translate that theory into real-world applications. I could not have completed this work without his support and guidance.

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Abstract

The United States Navy (USN) currently utilizes a Rapid Penetration Test (RPT) on both land and in water as the means to determine whether sufficient soil bearing capacity exists for piles in axial compression, prior to construction of the Elevated Causeway System (Modular) [ELCAS(M)] pile-supported pier system. The USN desires a replacement for the RPT because of issues with the method incorrectly classifying soils as well as the need to have a less labor-and-equipment-intensive method for geotechnical investigation.

The Multichannel Analysis of Surface Waves (MASW) method is selected herein as the potential replacement for the RPT. The MASW method is an existing, geophysical method for determining soil properties based upon the acquisition and analysis of seismic surface waves used to develop shear wave velocity profiles for the soils at specific sites. Correlations between shear wave velocity and Cone Penetration Testing are utilized to classify soils, develop pile blow count estimates, and calculate soil bearing capacity.

This researcher found that the MASW method was feasible and reliable in predicting the required properties for terrestrial sites. However, it was not successful in predicting those properties for underwater marine sites due to issues with equipment and field setup. Future areas of improvement are recommended to address these issues and, due to the success of the method on land, it is expected that once the issues are addressed the MASW method will be a reliable replacement for the RPT method across the entire subaerial and subaqueous profile.

Chapter 1: Introduction

During wartime operations or in response to humanitarian crises and natural disasters, the United States Navy (USN) is tasked with providing access to beachheads and coastal areas to ensure that a reliable flow of supplies and materials is available to support the crisis zone. Suitable piers, harbors, or other means of delivering logistics from ship to shore are typically non-existent, damaged, or insufficient in capability or capacity to meet the logistical demands of these missions. The Naval Facilities Engineering Command (NAVFAC) designed, procured, and maintains the Elevated Causeway System (Modular) [ELCAS(M)] as the primary means of providing access to coastal areas and ensuring logistical flow. The ELCAS(M) system serves as a portable pier system comprised of a beach ramp, an elevated roadway & pier section, and a pierhead that is supported by steel piles driven into the sea bottom. Currently, a Rapid Penetration Test (RPT) developed by NAVFAC is conducted by USN divers to determine whether acceptable marine soil bearing capacity in axial compression exists for the piles used to erect the ELCAS(M). In non-permissive or adverse environments that often occur during USN operations, as well as due to the manpower and material intensity of the RPT, diver safety can become highly compromised. The USN is seeking a methodology for determining acceptable marine soil bearing capacity in axial compression that reduces labor and equipment requirements and more accurately determines soil properties. For brevity, bearing capacity is used for the remainder of this thesis in place of "bearing capacity in axial compression".

In this thesis, the Multichannel Analysis of Surface Waves (MASW) method, an existing/non-invasive method utilized to estimate soil bearing capacity, is investigated as a replacement for the RPT. In the work described herein, concepts related to the development of the MASW method and its application underwater, the experimental setup to facilitate the method, and the execution of testing and analysis of the data acquired to determine the method's acceptability in determining accurate soil bearing capacity as a replacement for the RPT, are presented.

Chapter 2: Background & Literature Review

2.1 Seismic Waves

The Multichannel Analysis of Surface Waves (MASW) method relies on the acquisition and analysis of seismic surface waves to ascertain relevant geotechnical properties of the soils through which these surface waves travel. Seismic waves are energetic waves that are released by earthquakes, explosions, or other events imparting energy into the Earth and travel through and along the Earth's interior and surface. The two main types of seismic waves are body waves and surface waves. Body waves consist of compressional (primary or P) waves and shear (secondary or S) waves which travel both horizontally and vertically through the interior of the Earth. Surface waves, consisting of Rayleigh and Love waves, travel along and parallel to the interface of the Earth's surface and the atmosphere. The importance, and usefulness, of surface waves is based upon the relationship between surface waves and the velocity of propagation of body waves, with Rayleigh-like Scholte surface waves and shear wave velocities being of primary importance in this application. These relationships allow for a determination of geotechnical properties for the soils through which they travel and from which they are acquired. Figure 1 below provides a graphical visualization of P, S, and surface waves.

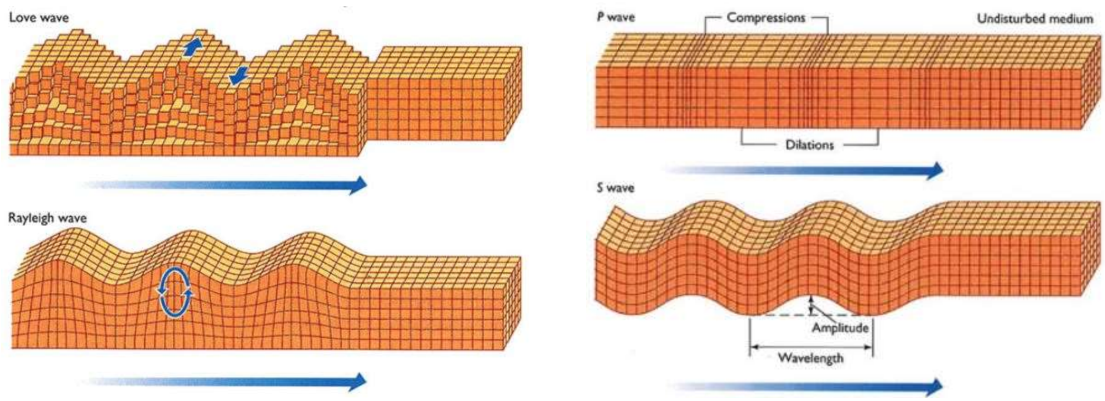


Figure 1. P, S, Love, and Rayleigh wave visualization. Reprinted from Incorporated Research Institutions for Seismology, Retrieved October 8, 2018, from http://www.iris.edu. Copyright 2018 by Incorporated Research Institutions for Seismology. Reprinted with permission.

2.2 Discovery and Development of Surface Wave Theory

Rayleigh (1885) was the first to formulate a mathematical expression for the second main type of seismic wave and the first to coin the term “surface wave”. At the time of the publication of his concepts, body wave theory was well developed but could not fully explain the seismic energy and arrival times of the waveforms for seismic events. Body waves are high frequency waves that occur relatively early in a seismic record, and they were well understood in Rayleigh’s time. However, delayed, lower frequency waves occurring later in the seismic record were identified but unformulated prior to his work. Rayleigh mathematically addressed surface waves as the outcome of vibrational waves occurring between a free surface and an elastic medium (air-solid interface) with an amplitude decreasing with depth and having velocities related to but slower than shear wave velocities. These Rayleigh waves are the result of interfering P- and S- waves in a soil stratum that, moving from left to right away from a source in a Cartesian coordinate system, move in an elliptical and counterclockwise motion, as shown in Figure 1. In his publication, Rayleigh noted the potential importance of such waves to seismic related research because the Earth and its atmosphere act as the elastic medium and free surface, respectively, along which seismic surface waves can be transmitted. Rayleigh's hypothesis as to the usefulness of surface waves has been validated, as Rayleigh waves have since been determined to be guided and dispersive waves whose phase-velocity through a layered earth model is a function of frequency, P-wave and S-wave velocities, density, and depth (Xia, Miller, & Park, 1999). Through the manipulation of these relationships, Rayleigh waves have become a powerful tool to use for characterizing a soil's structure and its related properties.

Stoneley (1924) extended the work of Rayleigh to include surface waves other than those at a free surface and elastic medium (air-solid interface). He formulated the presence of Rayleigh-like waves between two dissimilar elastic media, and of specific interest to geotechnical engineering, at the interface of two rock strata (solid-solid interface) in the interior of the earth.

Most applicable to this research, Scholte (1947) investigated limiting cases in which both Rayleigh and Stoneley waves could coexist in a layered system. The mathematical treatment devised by Scholte determined that surface waves could exist at the boundary of two media, one being a compressible solid (such as the soils in a marine subbottom) and the other being an incompressible medium (such as a fluid layer overlying the compressible solid). This treatment by Scholte, and its further development by Biot (1951), allowed for the application of Rayleigh's and Stoneley's previous formulations to fluid-solid surface waves termed "Scholte waves" or "Stoneley-Scholte" waves. The Scholte wave was shown to be directly related to shear wave velocities and Rayleigh wave velocities in marine sediments via both theoretical and field experiments by Stokoe, et. el., (1990) and Wright, et. al., (1991). Because of these relationships, and their underwater applicability, the Scholte wave is the surface wave type excited, acquired, and analyzed in this thesis in order to determine soil bearing capacity in the marine soils of interest.

2.3 Review of Historical Engineering Applications of Surface Wave Methods

A brief understanding of the basic equipment and processing flows for the surface wave methods to be discussed in this thesis is needed and are given below:

1) Receivers are deployed to acquire the surface wave signals (geophones on land or hydrophones underwater).
2) A wave generation source is actuated to initiate Rayleigh or Rayleigh-like surface waves in the medium being examined.
3) A data acquisition system is used to record signals from the receivers.
4) Computer or manual calculations are utilized to graph the resultant surface waves versus time and distance records, to develop a dispersion curve, and execute an inversion process for the record to develop soil parameters as a function of depth. Dispersion and inversion are discussed below.

Initial surface wave investigative methods were focused on terrestrial applications investigating pavements and associated subgrades as well as properties of layered soil strata. Later, they were later utilized for subaqueous applications. The following paragraphs discuss the historical evolution of surface wave methodologies.

The first attempt at utilizing surface waves as an investigative technique, called the Continuous Surface Wave (CSW) method, was developed by Van Poel (1951) and Jones (1955). Their CSW tests were simple tests in which a vibrator was set on a paved surface to be used as a steady-state, wave-generation source, and a single geophone was placed at progressively farther distances away from the source on the pavement to acquire the excited waves. This method was focused on capturing the deformation of pavement due to alternating loads as well as the rates of propagation of the induced vibrations and their relationships to the elasticity constants of the pavement. This method was improved upon from the 1950s through the early 1980s by advances in dispersion and inversion processing theory (discussed below) as well as by advances in computing technology to assist in mathematical calculations.

The next major advance was the Spectral Analysis of Surface Waves (SASW) method initially developed by Heisey, et. al., (1982) and formalized by Nazarian & Stokoe (1985) at the University of Texas at Austin. The focus of this method was to provide an improved process for determining elastic moduli of pavement systems and shear wave velocity profiles of soil sites. The fundamental aspects of the SASW method that differ from CSW were (1) the use of spectral analysis or a frequency-wave number domain versus a time domain representation of wave data; (2) an impulsive energy source instead of a steady-state source; and (3) using two receivers instead of a single receiver. Additionally, advances in dispersion analysis and inversion methods were utilized to develop shear wave velocity profiles of the soils being studied. In the SASW method, multiple wave records are combined to develop an experimental dispersion curve, which is a measure of phase velocity attenuation through a medium with depth or frequency. An inversion process, in which a theoretical dispersion curve is produced for the medium, and an objective function which is typically the root mean square difference between the theoretical and experimental dispersion curve, is minimized until acceptable agreement is obtained. This function is then used to match the experimental dispersion curve and the theoretical dispersion curve for the medium to create a shear wave velocity profile from which medium layer properties are inferred.

The advantages of the SASW method were that the two-receiver approach allowed for a better calculation of phase velocity because of the phase difference and spacing between the receivers. However, the two-receiver SASW method had numerous limitations including the influence of higher modes of the Rayleigh wave on the record, near and far field interference effects, contamination from reflected and direct surface and body waves, and the time-consuming necessity to change receiver spacing and location to overcome the above drawbacks.

2.4 Multistation Approaches to Surface Wave Methods

In order to mitigate the SASW limitations, multistation (more than two-receiver) methods were developed and are at present being utilized for surface wave-based investigations to develop shear wave velocity profiles and other medium properties. It is important to note that the earliest applications of the multistation approach were used to investigate subaqueous soil layers. The earliest implementors of a multistation approach for surface wave applications were McMechan & Yedlin (1981) and Gabriels, Snyder, & Nolet (1987). Although McMechan and Yedlin were primarily concerned with dispersive waves and their theoretical wave-field transformations, they relied on marine data obtained via multiple receivers for the experimental data against which they compared their synthetic or theoretical formulations. Their experimental data set was a marine dataset, and they discussed Rayleigh-like, or Scholte waves. Gabriels et al. (1987) further extended the use of a multistation approach by utilizing a 24-geophone receiver array in tidal flats in the southwest of the Netherlands explicitly to overcome the limitations of the SASW approach (specifically to prevent special aliasing and higher mode interference). The formalization of the multistation approach and its definition as a separate, unique surface wave method (the method upon which this thesis is based) was the MASW method developed during the mid to late 1990s by Park, Miller, & Xia (1999). Chapter 5 of this thesis provides key MASW concepts as well as the method's applicability to marine soils.

Although not utilized in this thesis, for completeness, the microtremor/ReMi approaches to wave measurements are discussed in the following. Microtremor/ReMi approaches take advantage of the same theory and equipment setup as the MASW method with the difference being that passive energy sources are used for wave generation instead of active sources. Active sources are sources that are single, primary means for generating wave energy for a specific data acquisition event, and the record for the event is based upon the known active source spacing and initial time, or time zero, of the energy generation. Microtremor/ReMi tests, on the other hand, rely on passive sources as their energy/wave generation sources. These sources are heavy vehicle traffic occurring on a nearby roadway, earthquakes, or other means of energy/wave generation that are present in the environment without deliberate imparting of energy into the soil for the purposes of testing. The exact space or time functions of these wave sources are indeterminate.

Chapter 3: Concepts

This thesis utilizes the linearly elastic nature of soils undergoing small strains to develop shear wave velocity profiles of the soils under investigation via the acquisition of seismic surface waves with the MASW method. The developed shear wave profiles are then used to classify the soils, are converted to standard penetration test (SPT-N) blow-counts, and other geotechnical property values through correlation relationships. Based upon these correlations, soil bearing capacity is determined utilizing procedures outlined in Thompson et al. (2012).

Prior to discussing MASW methodology and how the method develops shear wave velocity profiles in soil, the understanding of several key and related concepts discussed in the above paragraph is necessary. This chapter is broken into the following sections describing these concepts:

1) Theories of Elasticity and Shear Wave Velocity: Vs, G_{max}
2) Surface Wave Velocity Relationships: Vs, $V_{Rayleigh}$, and $V_{Scholte}$
3) Classification of Soils Based on Shear Wave Velocity (Vs) and the Cone Penetration Test (CPT)
4) Relationship between Shear Wave Velocity (Vs) and Standard Penetration Test (SPT) Blow Counts
5) Geotechnical Property Determination: Peak Friction Angle (ϕ'_p), Relative Density (D_r), buoyant unit weight (γ_b), and Undrained Shear Strength (S_u)
6) Synthesis: Vs, soil classification, SPT, and geotechnical properties to calculate bearing capacity

Chapter 4 provides an overview of the MASW methodology used to develop shear wave velocity profiles in soil in order to be able to apply the above concepts to determine soil bearing capacity.

3.1 Theories of Elasticity and Shear Wave Velocity: Vs, G_{max}

The theory and engineering application of seismic waves for soil investigation is based upon the theory of elasticity (Hookean model) and the principles of continuum mechanics. It is not the intent of this thesis to provide an in-depth review of the above-mentioned theories and principles but rather to present the applicable relationships between linear elasticity and seismic waves in soils. The reader is referred to excellent publications available such as Bullen (1985) or Novotny (1999) for additional information. Accordingly, the marine soils investigated in this thesis are considered homogenous, linear elastic, isotropic, and undergoing small strain dynamic cyclic loading.

Elastic soils are considered fully recoverable, in that, under very small strain level events (less than 10^{-3} percent in magnitude), no permanent deformation occurs, and the soil returns to its original state after loading. Strains imparted on a soil from seismic surface wave events are considered very small strain events, and this allows for treating the soil undergoing a seismic surface wave load as a linear elastic material (Hamilton, 1971; Luna & Jadi, 2000). Analyzing elastic soils undergoing dynamic, cyclic loading (such as a seismic wave) allows for the development of shear stress-strain relationship curves that exhibit hysteresis loops as shown in Figure 2.

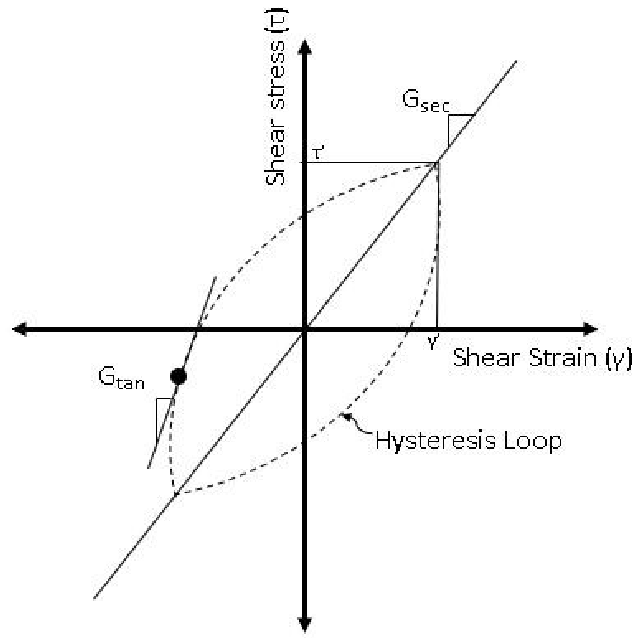


Figure 2. Generalized shear stress-strain hysteresis loop for elastic soil under cyclic loading

A hysteresis loop tracks the recoverable nature of an elastic soil in that it represents the stress-strain history, or path, of a soil as it experiences loading and unloading in a cyclic manner. The tangent shear modulus (G_{tan}), or the local slope of the loop, and secant shear modulus (G_{sec}), or the slope of the line connecting loci of the loop, shown in Figure 2 are two representations of the small-strain shear modulus of a soil. Shear moduli are important properties as they measure the resistance to deformation of soils undergoing shear stresses and resultant strains and are indicative of the shear stiffness of a soil. Shear moduli can, in turn, be correlated to soil type and strength properties of the soil.

As soils undergo different small-strain magnitudes under different cyclic loading conditions, hysteresis loops for each strain level can be combined to produce a composite stress-strain hysteresis loop graph as shown in Figure 3.

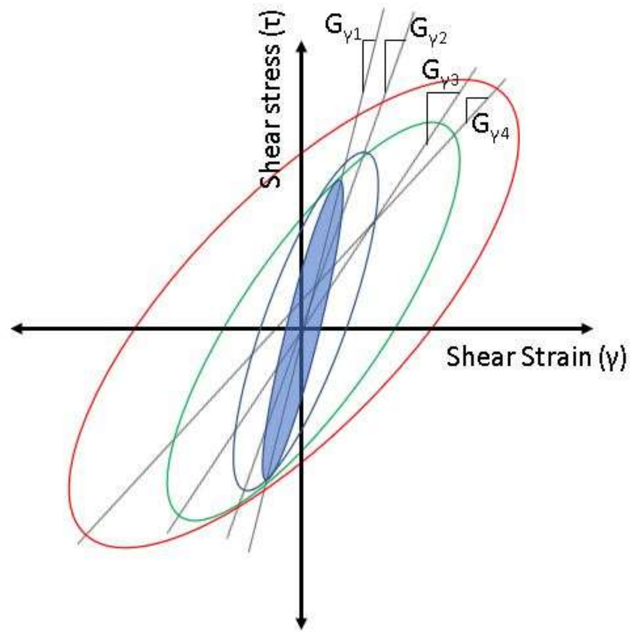


Figure 3. Composite shear stress-strain hysteresis loops for various strain loading conditions

The loci of the points, or tips, of the hysteresis loops can be combined into a "back bone" curve as shown in Figure 4.

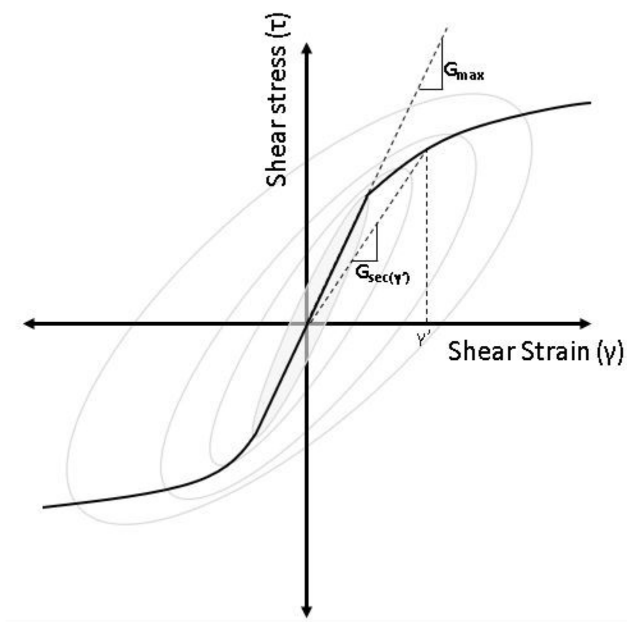


Figure 4. "Backbone" modulus reduction shear stress-strain curve

The slope of the backbone curve through the origin, identified as the point of zero strain, represents the maximum shear modulus of the soil, or G_{max}. With the assumption that the soil is a homogenous, isotropic, and linear elastic material, G_{max} is important because it allows for the application of the relationship between soil shear wave velocity and G_{max} developed for shear wave propagation in a linear elastic material (Love, 1892) given by:

$$Vs = \sqrt{\frac{G_{max}}{\rho}} \tag{3.1}$$

where G_{max} is as described and ρ is the soil mass density.

The relationship between Vs and G_{max} is key to surface wave methods, as Vs can be derived from Rayleigh and Scholte waves, which are the wave types analyzed during surface waves tests in this thesis. Furthermore, Vs and G_{max} are important in classifying soil types and their associated ranges of geotechnical properties, as they are both primarily functions of soil mass density (ρ), Poisson's ratio (υ), void ratio (e), and effective stress (σ') (Wair, DeJong, & Shantz, 2012). Deriving shear wave velocity (Vs) via the MASW method is the basis used to determine the bearing capacity of the soils investigated in this report because of its usefulness in classifying soil types and their engineering property ranges.

3.2 Surface Wave Velocity Relationships: Vs, $V_{Rayleigh}$, and $V_{Scholte}$

Rayleigh surface wave velocities ($V_{Rayleigh}$) and Scholte surface wave velocities ($V_{Scholte}$) and their relationship to shear wave velocity (Vs) are the foundational relationships utilized by the MASW method. The acquisition of these surface wave types and their inversions are used to develop shear wave velocity profiles. Richart, Hall, & Woods (1970) published correlations between Vs and $V_{Rayleigh}$ and this relationship is given by:

$$V_{Rayleigh} = (0.87 \rightarrow 0.95)Vs \quad (3.2)$$

The next key relationship used to apply MASW in marine soils is the relationship between $V_{Rayleigh}$ and $V_{Scholte}$. As discussed previously, Stokoe et al. (1990) and Wright et al. (1991) developed a range in the relationship between $V_{Rayleigh}$ and $V_{Scholte}$ for marine soils shown below:

$$V_{Schol} = (0.87 \rightarrow 0.99)V_{Rayleigh} \quad (3.3)$$

These shear and surface wave relationships and the relationship of Vs to the G_{max} of a soil are essential in the application of surface wave methods.

3.3 Classification of Soils Based on Shear Wave Velocity (Vs) and the Cone Penetration Test (CPT)

The Cone Penetration Test (CPT) is an in-situ, geotechnical test used to determine relevant geotechnical properties of the soils under investigation. The basic CPT setup consists of a metallic cone installed on the end of a series of rods which are pushed into a soil of interest at a constant rate. Measurements are made of the total pressure acting on the cone tip, termed the cone tip resistance [q_c (MPa)]. Additionally, a friction sleeve situated above the cone tip allows for measurements of total pressure acting on the friction sleeve, which are used to calculate sleeve resistance [f_s (kPa)] values. The CPT method utilizes q_c and f_s as the basis to characterize soils and determine their associated geotechnical properties. Forms of penetration for geotechnical property testing have been in use since the 1930s. The reader is referred to Robertson & Cabal (2015) as well as to ASTM D 5778-07: *Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils* for additional history and details of the CPT method.

Robertson (1986) developed the first Soil Behavior Type (SBT) charts that provided for the classification of soils utilizing q_c and f_s. His pioneering work in this field has been updated several times since initial publication, based upon additional field implementation and research, in 1990, 2009, 2010, and 2016 (Robertson, 1990; Robertson, 2009; Robertson, 2010; Robertson, 2016). Per Robertson (2016), the recommended SBT chart for soil classification using the CPT method is provided in Figure 5 below.

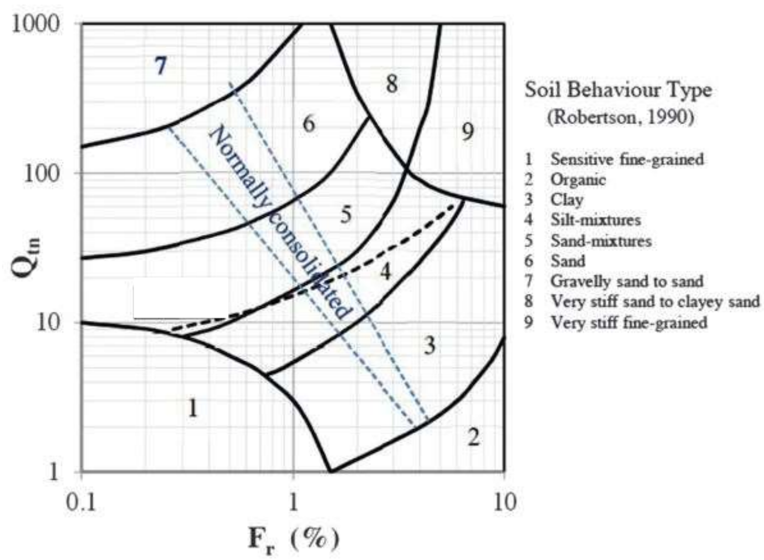


Figure 5. Soil behavioral type (SBT) chart, updated by Robertson (2009). Reprinted from "Cone penetration test (CPT)-based soil behaviour type (SBT) classification system – an update," by P.K. Robertson, 2016, *Canadian Geotechnical Journal, 53(12)*, p. 1910. Copyright (2016) by Canadian Science Publishing. Reprinted with permission.

Although this chart utilizes cone tip resistance (Q_{tn}) and Friction ratio (F_r %) normalized for pore water pressure and overburden stress in lieu of q_c and f_s, Robertson (2016) indicates that the chart can be successfully used to classify soils utilizing the basic q_c and f_s values via simplified relationships to estimate Q_{tn} and F_r percentages. In addition, correspondence with Lankelma, Inc., an industry leader in CPT testing both onshore and offshore, indicates that the SBT soil classification chart shown in Figure 5 can be used successfully for classifying both terrestrial and marine soils (J. Hobbes, personal communication, October 24, 2018).

The importance of the CPT method as it relates to this thesis is found in the correlation between Vs and CPT, q_c, and f_s values. Correlations from Wair, DeJong, & Shantz (2012) are utilized to determine CPT-SBT soil classification chart values, q_c and f_s, as given below:

$$V_s(m/s) = 118.8 \log(f_s) + 18.5 \quad (3.4)$$

$$V_s(m/s) = 32.3\, q_c^{0.089} f_s^{0.121} D^{0.215} \quad (3.5)$$

where q_c and f_s are in MPa and kPa, respectively, and as previously described, and D is depth of investigation. Utilizing the shear wave profiles developed via the MASW method, classification of the soils under investigation is accomplished utilizing these formulas and the chart shown in Figure 5.

3.4 Relationship between Shear Wave Velocity (Vs) and Standard Penetration Test (SPT) Blow Counts

The MASW testing conducted in this thesis utilizes *SurfSeis 6.0* software to develop 1-D shear wave and SPT blow count profiles. The *SurfSeis* software utilizes a Vs and SPT blow count correlation equation developed by Anbazhagan and Sitharam (2008) utilizing 741 SPT/boring log data pairs taken in India and Japan. The developed correlation equation is given below:

$$V_s = 78N_{1(60)}^{0.40} \quad (3.6)$$

where $N_{1(60)}$ is the SPT blow count corrected for 60% hammer efficiency and overburden stress.

There are also a variety of other Vs and SPT blow count correlation equations that have been developed, specifically as shown in Wair, DeJong, & Shantz (2012), but for the purposes of this thesis the Vs and SPT blow count correlation equation (3.6) built into the *SurfSeis* software is utilized. The need to determine SPT blow counts via Vs is discussed in Section 3.6 of this thesis.

3.5 Geotechnical Property Determination: Peak Effective Friction Angle (ϕ'_p), Relative Density (D_r), Buoyant Unit Weight (γ_b), and Undrained Shear Strength (S_u)

The bearing capacity equations utilized for this thesis require the knowledge of whether soils are plastic or granular. Determination of this is discussed in Section 3.6. Subsequently, the peak effective friction angle (ϕ'_p), relative density (D_r), and buoyant unit weight (γ_b) are needed for cohesionless soils, and the undrained shear strength (S_u) is needed for cohesive soils. Robertson (2009) and Robertson & Cabal (2015) are relied upon herein to determine these properties based upon the values of q_c and f_s derived from the shear wave velocity profiles of the soil as described in Section 3.3.

3.5.1 Peak effective friction angle. The chart shown in Figure 6 below is utilized to determine the peak effective friction angle (ϕ'_p).

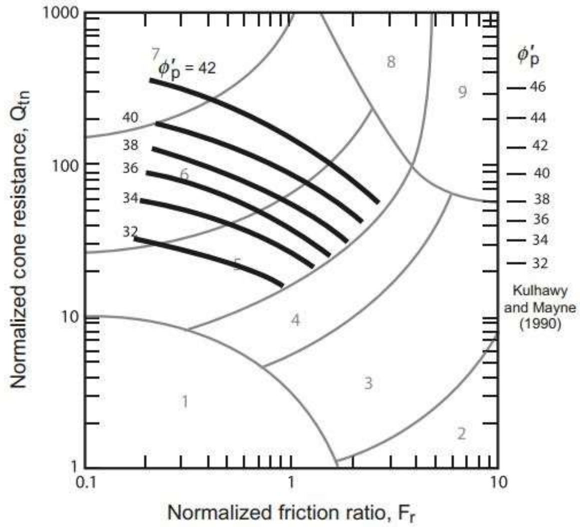


Figure 6. Peak effective friction angle chart. Reprinted from "Interpretation of cone penetration tests — a unified approach," by P.K. Robertson, 2009, *Canadian Geotechnical Journal, 46(11)*, p. 1337. Copyright (2009) by Canadian Science Publishing. Reprinted with permission.

3.5.2 Relative density. The correlation equation for relative density (Dr) given by Robertson & Cabal (2015) is

$$D_r^2 = \frac{q_c}{350}$$

$$Q_{tn} = f(q_c) \tag{3.7}$$

where Q_{tn} is the normalized cone tip resistance, discussed previously, that can be calculated as a function of q_c in its simplified form per Robertson (2016).

3.5.3 Buoyant unit weight. The buoyant unit weight (unit weight of saturated soil minus the unit weight of water) has a range of values associated with various soil types and is given in Table 1 below:

Table 1

Buoyant unit weight of various soil types (lb/ft³)

Soil Type	Min.	Avg.	Max.
Sand; clean / uniform / fine or medium	52	63	73
Silt; uniform / inorganic	51	62	73
Silty Sand	54	67	79
Silty Sand and Gravel	56	74	92
Sandy or Silty Clay	38	62	85
Silty Clay with Gravel; uniform	53	71	89
Clay	31	51	71

These values are from NAVFAC *Soil Mechanics Design Manual 7*.01. Once soils are classified using the chart shown in Figure 5, the average buoyant unit weight value is used in bearing capacity calculations for marine sites and similar bulk unit weight tables are used for terrestrial sites.

3.5.4 Undrained shear strength. Robertson (2009) provides a classification chart to determine the undrained shear strength (S_u) of plastic soils based upon the undrained shear strength ratio, which is given as a ratio of S_u to effective vertical stress, σ'_{vo}, as shown in Figure 7:

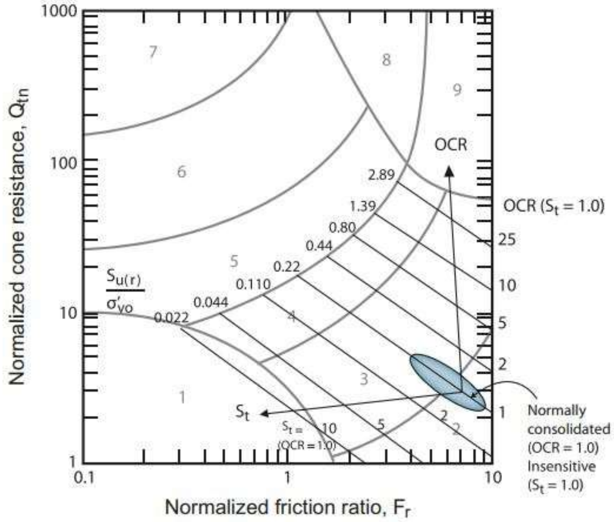


Figure 7. Undrained shear strength ratio chart. Reprinted from "Interpretation of cone penetration tests — a unified approach," by P.K. Robertson, 2009, *Canadian Geotechnical Journal, 46(11)*, p. 1337. Copyright (2009) by Canadian Science Publishing. Reprinted with permission.

To determine S_u, σ'_{vo} is calculated based upon the unit weights and depths of soils under investigation, and the ratio from the chart in Figure 7 is applied to calculate S_u.

3.6 Synthesis: Vs, Soil Classification, SPT, and Geotechnical Properties to Calculate Bearing Capacity

Based on the concepts presented in Sections 3.1 through 3.5, the process flow for determining bearing capacity utilizing the MASW method is as follows:

1) Determine shear wave velocity profiles of soils under investigation utilizing MASW methodology (discussed in Chapter 4).
2) Classify soils utilizing CPT-SBT soil classification charts to determine whether soils under investigation are plastic or granular.
3) Utilizing Robertson (2009) and Robertson & Cabal (2015) correlations, determine peak effective friction angle (ϕ'_p), relative density (D_r), and buoyant unit weight (γ_b)

for granular soils. Utilize bulk unit weight if on terrestrial sites. Determine undrained shear strength (S_u) for plastic soils.

4) Calculate expected SPT blow count profiles based upon shear wave velocity and SPT correlations to confirm soil property ranges given in Thompson (2012) and as a comparison to blow count profiles developed by the RPT method and ground truth pile driving logs.
5) Utilize Thompson (2012) bearing capacity formulas to determine load bearing capacity of soils.

The sites investigated in this thesis consist of one (1) terrestrial site and two (2) marine sites. These sites are discussed in Chapter 4. Thompson (2012) is the NAVFAC *Handbook for Marine Geotechnical Engineering* that the USN engineering community utilizes for marine engineering and design. This handbook can be used to determine appropriate pile bearing capacity in both terrestrial and marine applications. It is the primary reference used in order to ensure that all bearing capacity calculations conducted in this thesis are in accordance with USN standards. For the sake of brevity, the associated equations used to calculate bearing capacity are not included in this thesis. These equations are based on geotechnical theory and application formulated by G.G. Meyerhoff and K.Terghazi, among others, starting in the 1950s and continuing through to the present day. Appendix A includes the flow chart utilized by NAVFAC and this thesis to execute pile bearing capacity calculations along with pertinent properties and symbology used. Readers are referred to Thompson (2012) for the detailed calculation steps used in determining pile bearing capacity.

Chapter 4: Methods and Data Collection

This chapter is divided into two sections. The first discusses the equipment utilized to execute the MASW method, and important MASW analysis concepts employed to determine shear wave velocity profiles for the soils under investigation (applying the concepts discussed in Chapter 3, Sections 3.1 through 3.5). The second section discusses the sites and field data collection investigated in this thesis.

4.1 MASW Methodology

Utilizing the MASW methodology to determine shear wave velocity profiles for a soil under investigation falls into three procedural steps:

1) Acquisition of experimental data
2) Signal processing to obtain an experimental dispersion curve
3) Inversion processing to estimate site properties

Each of these steps is described in detail in the following sections. Although the MASW method was initially developed by Park, Miller, & Xia (1999) for land-based application, Kaufmann, et. al. (2005) and other investigators have successfully applied MASW to a marine environment.

4.1.1 Data acquisition. The MASW equipment setup utilized in this thesis for data acquisition consists of the following items:

1) Seismic sources. The sources of energy used to induce seismic surface waves in the soils under investigation for this thesis consisted of 1) a 20-lb sledgehammer and a

steel plate for terrestrial sites, and 2) a tubular steel mechanism devised to ignite blank, 12-gauge, 126 decibel, shotgun shell cartridges for the marine investigation sites. The sledgehammer is struck against the steel plate for the terrestrial source of waves, and a blank, 12-gauge, shotgun shell is fired into the seabed soil for the marine source. The sources are shown in Figure 8 below.

(a)  (b) 

Figure 8. Seismic sources. (a) Seismic source for terrestrial sites. (b) Seismic source for marine sites.

(b) Geophones. The equipment used to sense and acquire the surface wave signal induced by the seismic source for this thesis were OYO Geospace® 4.5 Hz geophones for terrestrial sites and OYO Geospace® MP-25 10 Hz hydrophones for marine sites. Twenty-four geophones and twenty-four hydrophones were set at 5-meter and 3-meter spacings, respectively, along a common carrier line. The receivers are shown in Figure 9 below.

(a)  (b) 

Figure 9. Receivers. (a) OYO 4.5 Hz geophones (b) MP-25 10 Hz hydrophones

(c) Seismograph. The seismograph used in this thesis for data acquisition was the Geometrics® Geode Exploration 24-channel seismograph shown in Figure 10 below.

Figure 10. Geode Exploration Seismograph with associated cabling

(d) Seismograph controller and data logging software. The program utilized to control the seismograph software in order to begin test recording, end test recording, log, and save acquired seismic trace profiles was the Geometrics®

Seismodule Controller software uploaded onto a Panasonic® Toughbook laptop. It is shown in Figure 11 below.

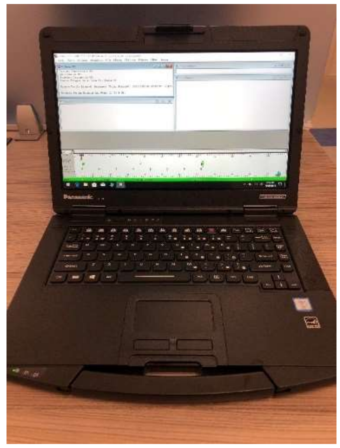


Figure 11. Seismodule controller software uploaded onto Panasonic® laptop

A generalized equipment layout of the above MASW components in the field is given in Figures 12 and 13 below.

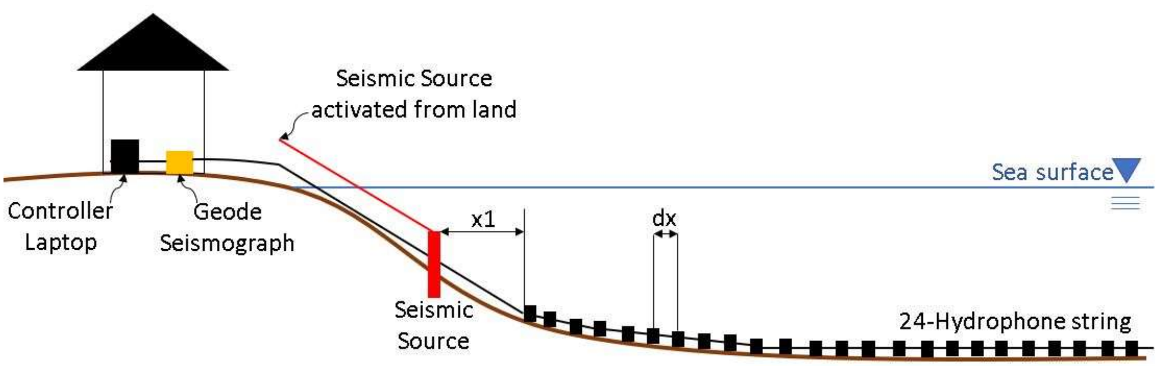


Figure 12. Generalized MASW equipment setup for marine sites

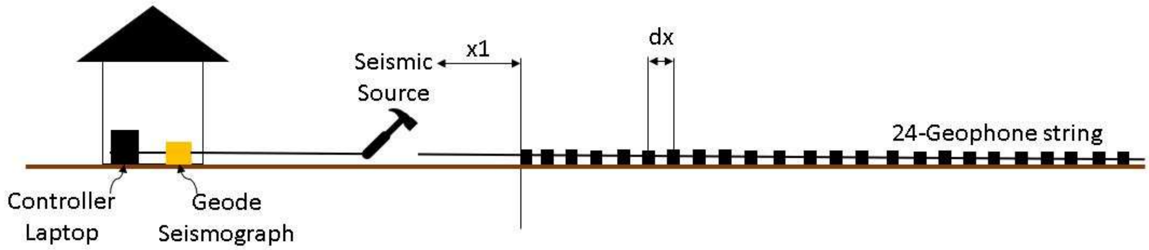


Figure 13. Generalized MASW equipment setup for terrestrial sites

Using the MASW method, the depth of the investigation is controlled by the distance from the seismic source to the first receiver (denoted as x1 in Figures 12 & 13) and the spacing between receivers (denoted as dx). Park, Miller, & Miura (2002) published optimum field parameters for the MASW field setup based upon desired depth of investigation in order to assist MASW field operators. The desired depth of investigation for this thesis is 65 ft (19.8 m), based upon past ELCAS(M) pile embedment depths that have been recorded across a range of soil types. It is assumed that developing allowable bearing capacity profiles to this depth via the MASW method is suitable for comparison to the current RPT method of investigation. The field equipment parameters used in this thesis for all testing locations are summarized in Table 2 below.

Table 2

MASW Field Setup Parameters

Depth of Investigation (m)	Receiver (Hz)	Source Offset (x1) (m)	Receiver Spacing (dx) (m)
20 - 30	4.5/10	10.0	3.0/5.0

4.1.2 Dispersion analysis. Surface wave velocity depends on the material properties of the soil through which seismic waves travel. Surface waves of different frequencies travel at different velocities depending on variations in soil heterogeneity. This phenomenon, i.e. the variation in travel velocity through the depth of a soil profile, is known as "dispersion". The surface wave method takes advantage of this velocity dispersion to identify and characterize the soils through which the test wave travels.

Dispersion analysis for MASW seismic events is accomplished by using the *SurfSeis* software developed by the Kansas Geological Survey. The *SurfSeis* software utilizes the phase shift method to image and extract dispersion curves for a given seismic record and transforms them from offset-time (x:t) domain traces to frequency-phase velocity ($f{:}c_w$) traces representing the dispersion of the surface waves through the soil. The phase shift method can be broken down into the following steps (Park, Miller, & Xia, 1998):

1) Fast Fourier Transform (FFT). The seismic record acquired by the seismograph is represented in the offset (x)– time (t) domain. Applying FFT to this record allows the data to be represented in the offset (x) – frequency (f) domain:

$$FFT\ u(x,t) \rightarrow U(x,f) \tag{4.1}$$

2) Amplitude normalization. The x-f domain can be represented as a function of both the phase (Ph) and amplitude (A) spectrums of the frequency in the same domain.

$$U(x,f) = Ph(x,f)A(x,f) \tag{4.2}$$

The phase spectrum can be related to a phi (∅) value and the equation is thus recast as

$$U(x,f) = e^{-i\emptyset x}A(x,f) \tag{4.3}$$

where $\emptyset = f/c_w$, c_w = phase velocity for frequency, f.

3) An integral transformation is performed on U(x, f) to transform it to a V(f, ϕ) representation of the wavefield. The ϕ value redefines Ø as the maximum value of Ø over a summation of various frequencies of the given wave fields, in lieu of a single frequency, and replaces Ø in the formula (i.e., $\phi = f / c_w$). For the values of ϕ where these maximums occur, the phase velocity (c_w) can be determined for a given frequency (f), and a new wavefield representing these peak ϕ/phase velocities is transformed into a frequency-phase velocity domain, I(f, c_w) and then plotted. This plotted I(f, c_w) domain now represents the dispersion of the surface waves through the medium at various frequencies and phase velocities (speeds at which the frequencies disperse). A generalized graphical representation of the results of the dispersion analysis is given in Figure 14 below.

(a) (b)

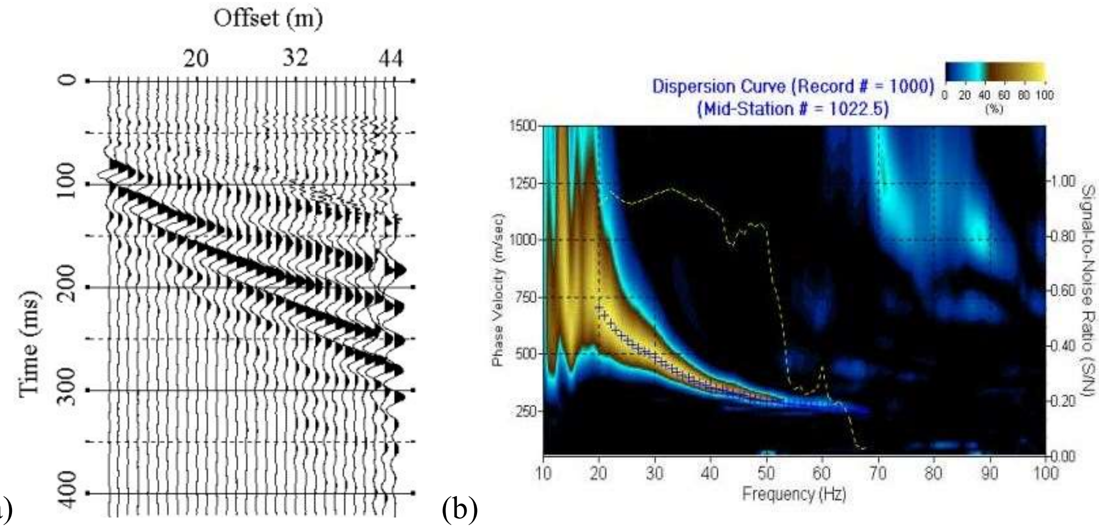


Figure 14. Seismic Record & Dispersion Curve. (a) Typical seismic record acquired from seismograph. (b) Dispersion curve of phase velocity versus frequency after dispersion analysis. Reprinted from Kansas Geological Survey, Retrieved October 25, 2018, from http://www.kgs.ku.edu. Copyright 2018 by Kansas Geological Survey. Reprinted with permission.

4.1.3 Inversion. Inversion modelling can, in general, be described as a process whereby the known results of an experiment are utilized to provide an estimate of causes for those results. Conversely, a forward model is one in which results are estimated based upon the known causes in the experimental setup. As applied to the MASW method, the *SurfSeis* software utilizes a forward modeling approach to solve the inverse problem of determining a shear wave velocity profile of a soil site in a process developed by Xia, Miller, & Park (1999). The general forward/inversion process utilized in *SurfSeis* is as follows:

1) Develop a theoretical forward earth model based upon assumed densities (ρ), compressional wave velocities (Vp), shear wave velocities (Vs), Poisson's ratio (ν), and thickness of layers (h).

2) Utilizing Knopoff's method (Schwab & Knopoff, 1972), develop a theoretical dispersion curve based upon the assumed properties. Xia, Miller, & Park (1999) determined that Vs is the dominant property affecting changes in dispersion of surface waves, and it is the one property that is adjusted throughout the inversion process while the other properties listed above are held constant.
3) Compare the theoretical dispersion curve to the experimental dispersion curve developed from the actual field data/surface wave measurements at the soil site. A root mean square (RMS) function calculates the deviation between the calculated theoretical dispersion curve and acquired experimental dispersion curve.
4) If the RMS value is above the error threshold built into the *SurfSeis* software, the Vs values in the theoretical model are automatically adjusted, and a new theoretical dispersion curve is developed.
5) This process continues until the RMS error falls within acceptable limits, and the final forward model is considered to be the solution to the inverse problem. The associated Vs profile of the final forward model is then presented as the actual Vs profile for the soil site.
6) Based upon the final Vs profile, the final Vp, density, layer thickness, and Poisson's ratios for the site are also updated based upon correlation equations between Vs and these properties. These correlations are given in the equations below and are the result of treating the soils under investigation as linear elastic:

$$\frac{V_P^2}{V_S^2} = \frac{2(1-\nu)}{(1-2\nu)} \tag{4.4}$$

$$Vs = \sqrt{\frac{G_{max}}{\rho}} \tag{4.5}$$

where 'ν' is Poisson's ratio, 'ρ' is density, and G_{max} is as previously discussed.

The SurfSeis software allows for the inversion of Rayleigh surface waves and Scholte surface waves based upon the site of investigation. Scholte surface waves are inverted based upon water depths at the sites of investigation, which are input into the software by the user. All other inversion steps for Scholte surface waves are the same as for Rayleigh surface waves and as discussed above.

To accurately constrain the assumed initial forward model for the *SurfSeis* inversion process, initial values of bulk or buoyant unit weight, Vp, and Poisson's ratio must be input into the forward earth model. It is important to note that Xia, Miller, & Park (1999) indicate that variances of 25% or less in density and Vp have minimal effects on the inversion process. Furthermore, the inversion process is not highly sensitive to initial thickness of layers (h). The model initially begins with a 10-layer model of assumed thicknesses. Although the sensitivity of the inversion process to density, Vp, Poisson's ratio, and layer thickness is low, the properties are constrained by utilizing accurate published values and correlations. The method used to determine initial densities, Vp, and Poisson's ratios for terrestrial and marine sites is given below:

1) <u>Terrestrial sites:</u> The *SurfSeis* software assumes initial Poisson's ratio for terrestrial sites to be 0.40. Based upon elastic correlations between Poisson's ratio, Vp, and Vs,

an assumed Vp profile is calculated for the soil site. Initial density is then calculated using Gardner's equation (Gardner, Gardner, & Gregory, 1974), shown below:

$$\rho(g/cm^3) = 0.23Vp^{0.25} \tag{4.6}$$

Poisson's ratio, density, and Vp are then updated at the end of the inversion process based upon the final Vs profile that is developed.

2) Marine sites: Average Poisson's ratio, buoyant density, and Vp values across all marine soil types was used in the marine site analysis as summarized in Hamilton (1971). Effort was made to ensure that the average values used in the model stayed within the 25% threshold for accuracy of the individual values for sand, silt, and clay. Table 3 below indicates the initial assumed values that were used in the forward model for marine site inversion purposes:

Table 3

Assumed Forward Model Values

Vp (m/s)	Density (g/cm^3)	Poisson's Ratio (υ) (non-dimensional)
1644	1.72	0.48

Assuming these initial forward model values, the final Vs profile developed by the *SurfSeis* inversion process for terrestrial and marine sites was used to calculate soil bearing capacity using the soil property correlations as discussed in Chapter 4.

4.2 Data Collection

The data collection component of this thesis consisted of conducting the MASW method at the same locations where existing RPT method investigations were conducted in early 2018. 1-D shear wave profiles were developed at each RPT site utilizing the MASW method. Chapters 5 and 6 present and discuss the results of this data collection, and the accuracy of MASW in predicting bearing capacity and SPT blow counts as compared with the RPT method based upon pile driving records available for the sites.

Three RPT method investigations were executed in Virginia Beach, Virginia at Joint Expeditionary Base Little Creek-Fort Story on 28 February 2018, and 6 March 2018. The locations of the RPT investigations are shown in Figure 15.

Figure 15. RPT Test Locations. (a) RPT #1: 36°55'37.5"N 76°09'53.1"W (onshore). (b) RPT #2: 36°55'38.1"N 76°09'53.0"W (surf zone). (c) RPT #3: 36°55'38.5"N 76°09'52.4"W (offshore)

Soils in this area have been classified as primarily clean sands (SW/SP) at surface level transitioning to sands with fines (SM/SC) and marine shell fragments at depth.

The MASW method was conducted at each RPT location on November 5th and 6th, 2018. The MASW geophone and hydrophone strings were centered over the coordinates of each of the RPT locations in order to develop 1-D shear wave profiles at the precise locations of RPT testing. One day was dedicated to the terrestrial RPT site and one day was dedicated to the marine RPT sites. The typical collection schedule for each day consisted of seismic record acquisition from dawn until noon, and seismic record analysis from noon until evening time. MASW data collection at these sites is summarized below:

1) MASW Site #1: The MASW method at RPT Site #1 was conducted on November 5, 2018. MASW Site #1 was the only onshore RPT location where MASW was executed. Layout of MASW field setup at MASW Site #1 is provided in Figure 16.

Figure 16. MASW setup at MASW Site #1

2) MASW Site #2: The MASW method at RPT Site #2 was conducted on November 6, 2018. High tides occurred at 5:29 AM and 5:46 PM. Low tide occurred at 11:48 AM. Water depth in the surf zone ranged from 0 cm to 15 cm. Layout of MASW field setup at MASW Site #2 is provided in Figure 17.

Figure 17. MASW setup at MASW Site #2

3) MASW Site #3: MASW method at RPT Site #3 was conducted on November 6, 2018. MASW Site #3 was located 10 meters offshore from MASW Site #2 in water 1 meter in depth. Layout of MASW field setup at MASW Site #3 is provided in Figure 18.

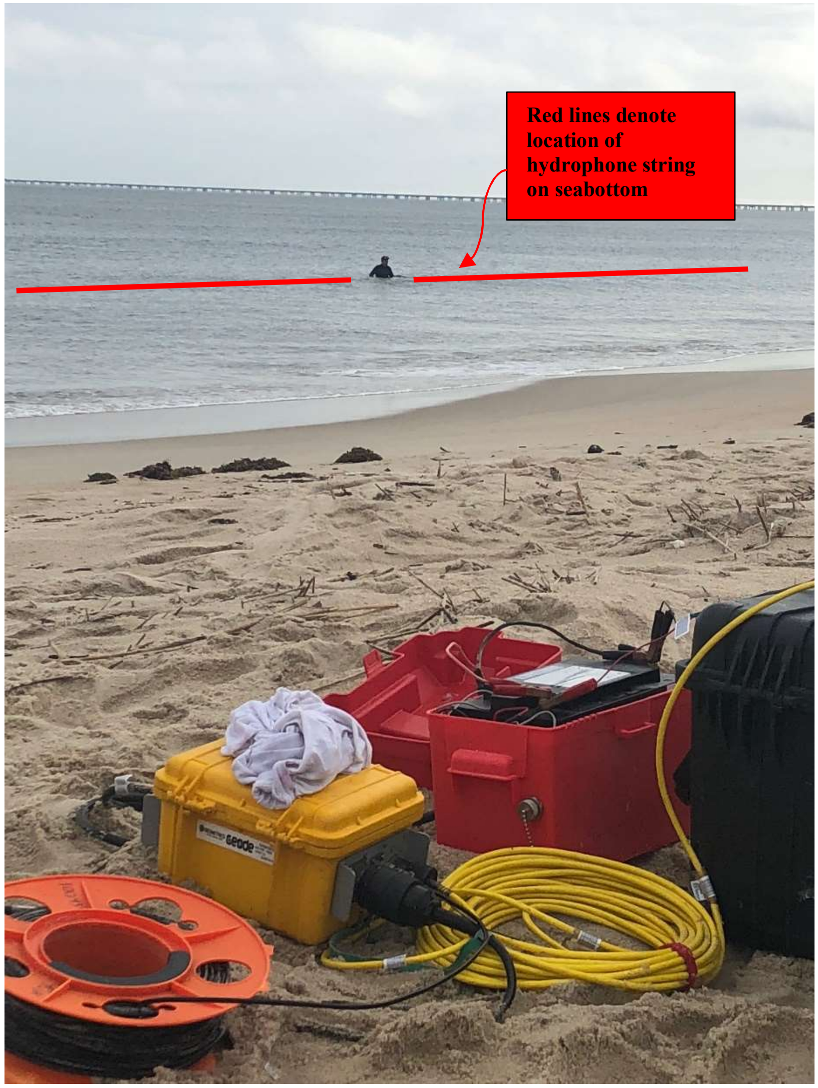


Figure 18. MASW setup at MASW Site #3 with seismograph in foreground

The results of the seismic record acquisition and analysis for each MASW site are presented in Chapter 5.

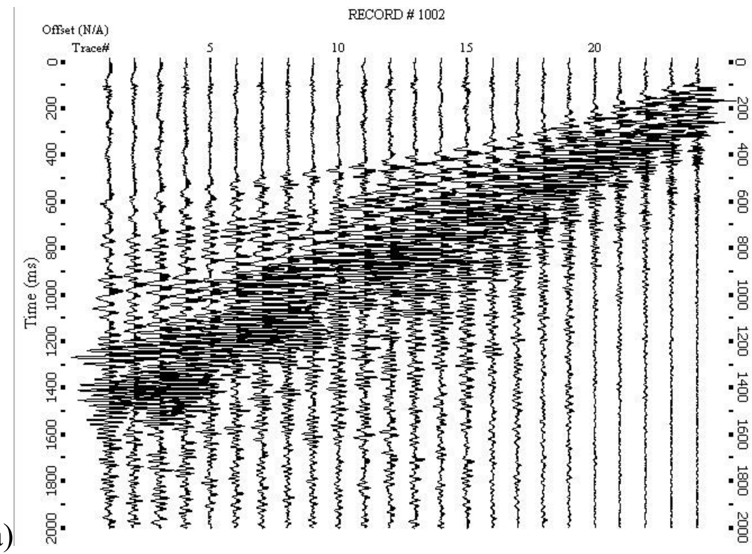
Chapter 5: Results

The results for this chapter are presented in sections for each respective RPT and MASW test site. The predicted soil type, blow count, and bearing capacity determined via the MASW method is compared with these values predicted by the RPT method. The values for each respective method are then compared with the pile driving logs available for each of these sites to determine the accuracy of the RPT and MASW methods in predicting actual field conditions. It must be noted that the pile driving logs only calculate blow count per foot and do not show a bearing capacity value. Per NAVFAC instructions, appropriate pile bearing capacity of 100 tons is expected when a blow count of 37 blows per foot is achieved. Therefore, the pile driving logs for these sites only provide data on the depth at which 37 blows per foot was achieved. This method of solely meeting the required blow counts per foot is an expedient means for USN field operators to determine that acceptable pile bearing capacity depth has been met when erecting the ELCAS(M). The pile driving logs are provided in Appendix B.

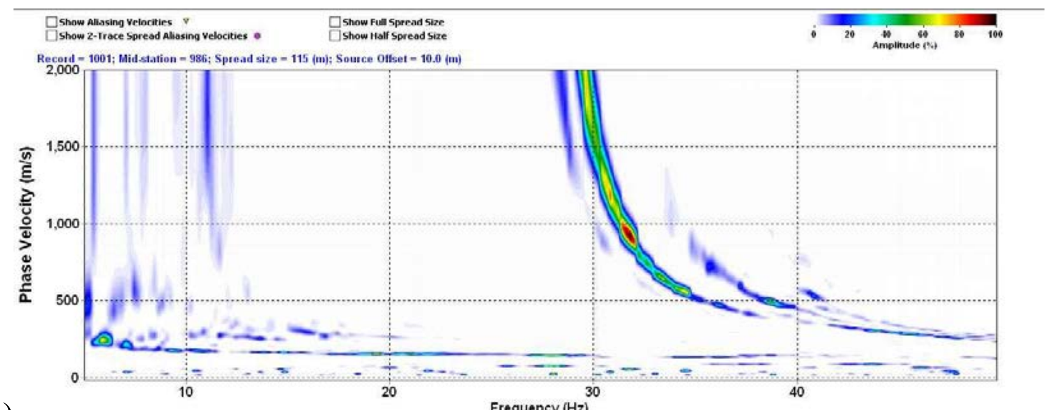
5.1 RPT/MASW Site #1 – Onshore

The calculations used to determine soil type, blow count, and bearing capacity for this site via the MASW and RPT methods are provided in Appendix C. The following section presents only the results of these calculations.

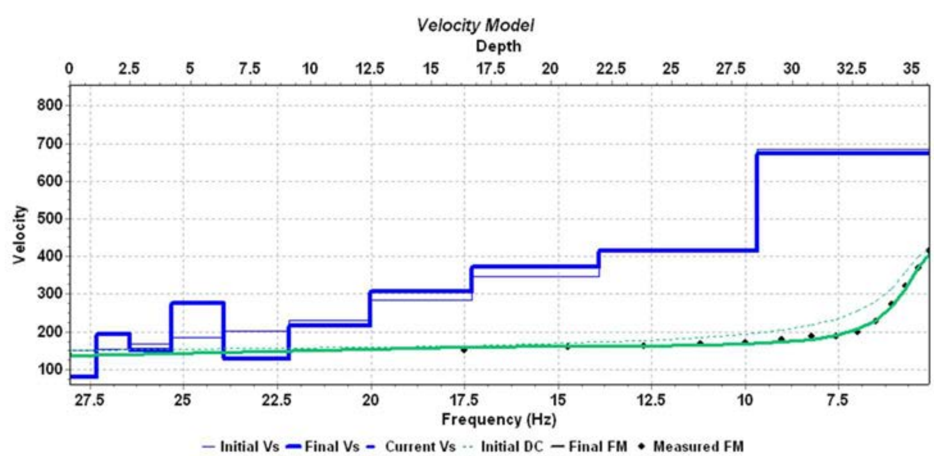
The seismic record, dispersion curve, and final Vs profile determined by the MASW method for Site #1are provided in Figure 19 below.



(a)



(b)



(c)

Figure 19. MASW results for RPT/MASW Site #1. (a) Seismic record (b) Dispersion Curve (c) Vs profile with depth

Analysis of this data by the *SurfSeis* software indicated that the overall quality of the seismic input data was excellent, the risk of contamination from higher modes was low, and that the overall signal-to-noise ratio was excellent. Comparison results are given in Table 4 below. Bearing capacity was calculated based on granular soils.

Table 4

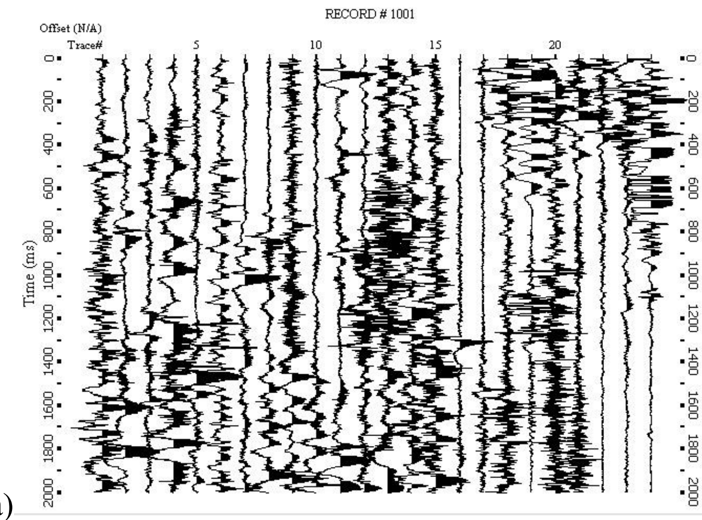
RPT/MASW Site #1: MASW, RPT, and pile driving log comparison

Investigation Method	Soil Type (USCS)	Depth @ 37 blows/ft (ft)	Bearing Capacity @ 37 blow/ft depth (tons)	Percent accuracy of depth @ 37 blows/ft as compared to pile driving log (abs│%│)
MASW	SC/SM, ML	63.4	404	~25%
RPT	SM	36.0	90	~31%
Pile Driving Log	---	51.8	---	---

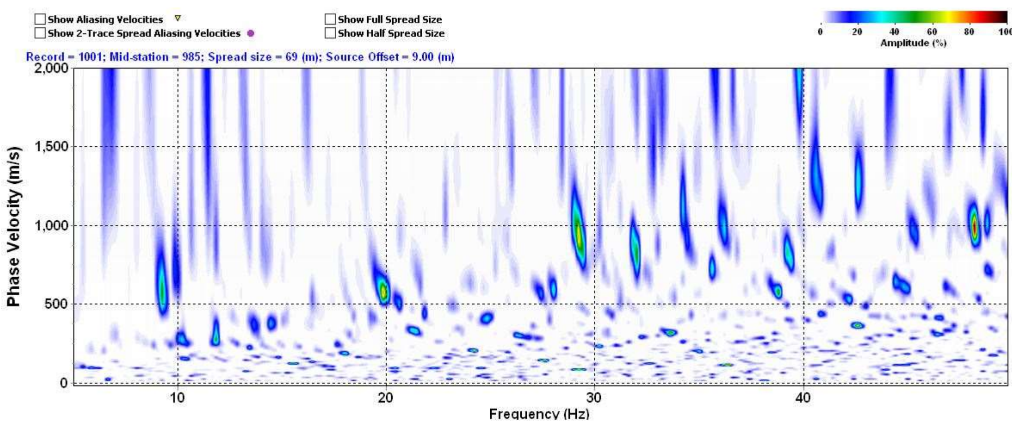
5.2 RPT/MASW Site #2 – Surfzone

The calculations used to determine soil type, blow count, and bearing capacity for this site via the MASW and RPT methods are provided in Appendix D. The following section presents only the results of these calculations.

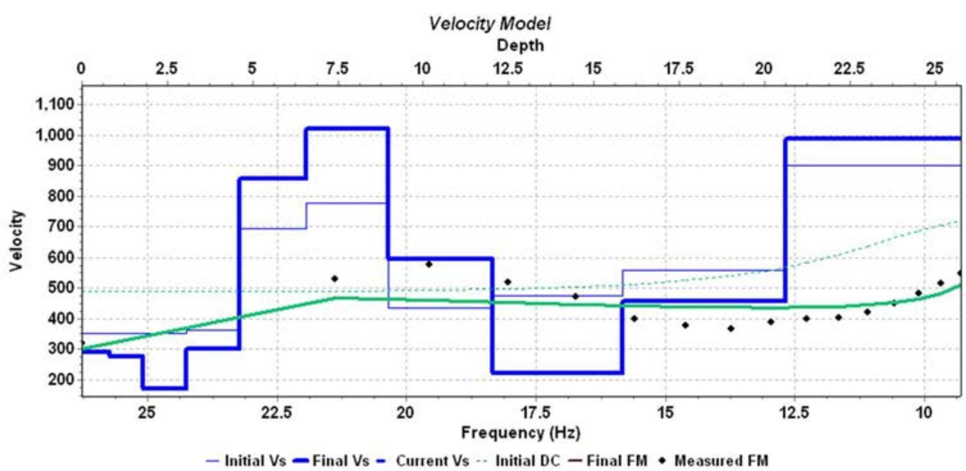
The seismic record, dispersion curve, and final Vs profile determined by the MASW method for Site #2 are provided in Figure 20 below.



(a)



(b)



(c)

Figure 20. MASW results for RPT/MASW Site #2. (a) Seismic record (b) Dispersion Curve (c) Vs profile with depth

Analysis of this data by the *SurfSeis* software indicated that the overall quality of the seismic input data was excellent and the risk of contamination from higher modes was low but that the overall signal-to-noise ratio was poor. Performing the dispersion and inversion analysis of the data at this location was problematic as there was very little trace or dispersive energy identified for the analysis. As such, it was determined that the data for this location was invalid, but an inversion analysis was still performed. Comparison results are given in Table 5 below. Bearing capacity was calculated based on granular soils.

Table 5

RPT/MASW Site #2: MASW, RPT, and pile driving log comparison

Investigation Method	Soil Type (USCS)	Depth @ 37 blows/ft (ft)	Bearing Capacity @ 37 blow/ft depth (tons)	Percent accuracy of depth @ 37 blows/ft as compared to pile driving log (abs│%│)
MASW	SC/SM, ML	16.8	178	~68%
RPT	SM	18.0	120	~65%
Pile Driving Log	---	51.8	---	---

5.3 RPT/MASW Site #3 – Offshore

The calculations used to determine soil type, blow count, and bearing capacity for this site via the MASW and RPT methods are provided in Appendix E. The following section presents only the results of these calculations.

The seismic record, dispersion curve, and final Vs profile determined by the MASW method for Site #3 are provided in Figure 21 below.

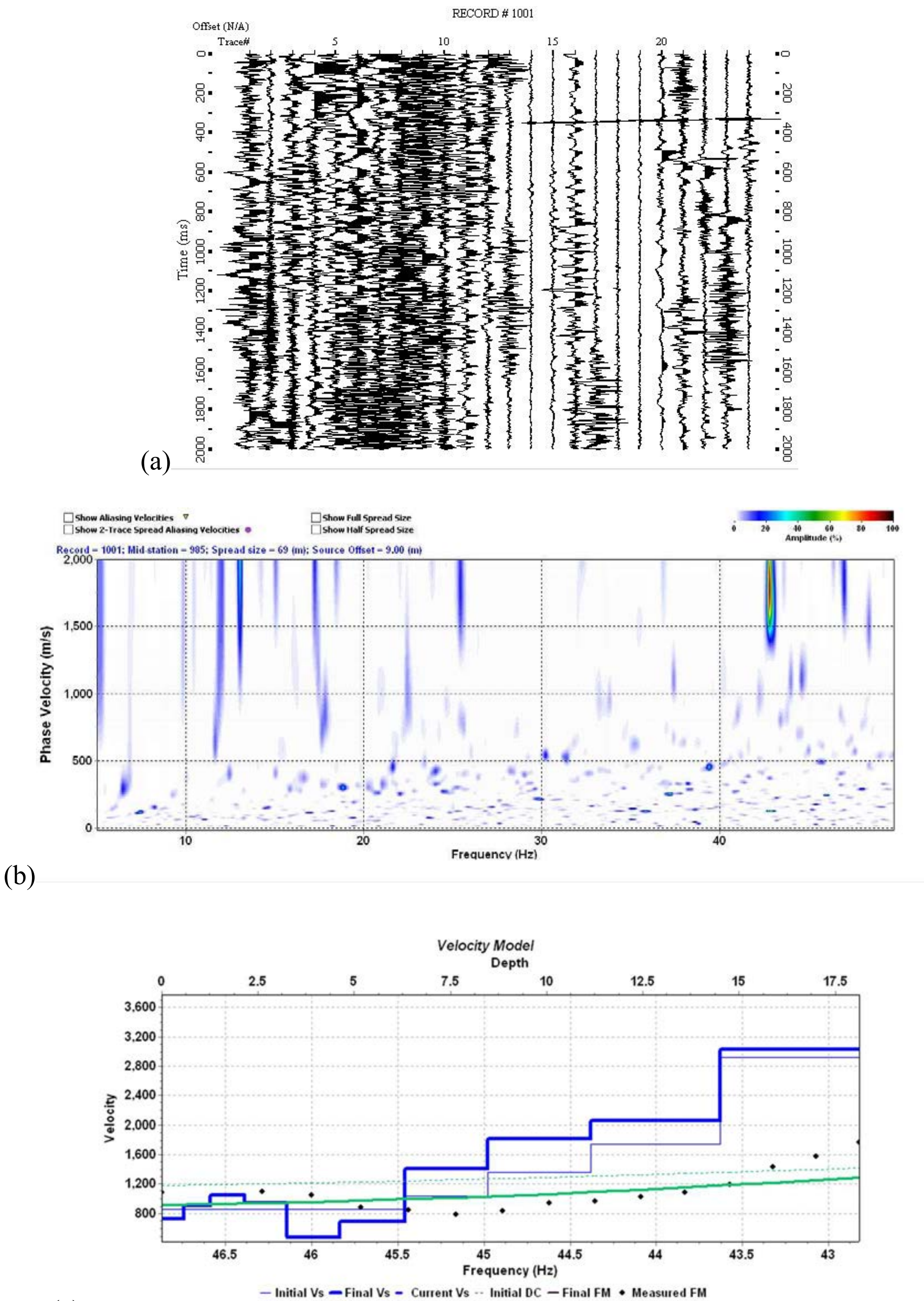


Figure 21. MASW results for RPT/MASW Site #3. (a) Seismic record (b) Dispersion Curve (c) Vs profile with depth

Analysis of this data by the *SurfSeis* software indicated that the overall quality of the seismic input data was poor, the risk of contamination from higher modes was high, and that the overall signal-to-noise ratio was poor. Performing the dispersion and inversion analysis of the data at this location was problematic as the seismic signal was so poor, and there was very little trace or dispersive energy identified for the analysis. Furthermore, the *SurfSeis* software was unable to detect a surface wave trend in the data. As such, it was determined that the data for this location was invalid, but an inversion analysis was still performed. Inversion produced unrealistic values for Vs velocities and SPT-N blow counts. Comparison results are given in Table 6 below. Bearing capacity was calculated based on granular soils.

Table 6

RPT/MASW Site #3: MASW, RPT, and pile driving log comparison

Investigation Method	Soil Type (USCS)	Depth @ 37 blows/ft (ft)	Bearing Capacity @ 37 blow/ft depth (tons)	Percent accuracy of depth @ 37 blows/ft as compared to pile driving log (abs│%│)
MASW	SC/SM/ML (assumed)	6.10	177	~88%
RPT	SM	34.0	100	~34%
Pile Driving Log	---	51.8	---	---

Chapter 6: Discussion

Each RPT/MASW site is discussed individually in the following chapter. The accuracy of the MASW method in determining pertinent site properties versus the RPT method, commentary on the field work and equipment deployment, and recommendations for future improvement are included in the discussion for each test site.

6.1 RPT/MASW Site #1 – Onshore

Confidence in the validity of results of the MASW method was the greatest at Site #1. The seismic record for this site represents a clear transmission of the surface wave form and energy through the soil strata and the initial analysis of the data by the *SurfSeis* software indicated that the data quality was good. (See *Figure 19*). The seismic record allowed the *SurfSeis* software to produce a dispersion curve that was unambiguous in its dispersive trend. This allowed for a confident selection of the fundamental mode of dispersion that was used for inversion processing. The soil classification, developed shear wave velocity profile, derived blow count profile, and calculated bearing capacity for this site were realistic and as expected of a predominantly sandy profile based upon comparison of published blow count and shear wave velocity values for sandy profiles. The MASW method was slightly more accurate than the RPT method in predicting the depth at which 37 blows/foot would be realized based upon the pile driving logs from the site. Furthermore, the MASW method predicted a more than acceptable 400-ton soil bearing capacity at the predicted 37 blows/foot depth, whereas the RPT method predicted a less than acceptable bearing capacity at its predicted depth of 37 blows/foot. There were no difficulties in deploying the field equipment for the onshore site or other items of note in the physical setup. Based upon these results, it is my opinion that the MASW method can be used as a reliable means for soil classification, predicting blow counts, and determining acceptable soil bearing capacity for ELCAS(M) pile driving at terrestrial locations.

Although there was some confidence in the results of the MASW method at Site #1, several recommendations for future study, specific to Site #1/terrestrial sites, are given below:

1) Conduct the MASW method at several additional terrestrial sites to build a larger data set and repository of MASW and RPT comparisons.
2) Increase the amount of "stacking" during seismic surface wave acquisition. Stacking is a function in the acquisition software that allows for multiple active impacts to be "added" together to create one seismic record. Stacking allows the software to focus its data acquisition on only those waves detected due to an active impact and remove extraneous, non-related passive waves and energy sources that have the potential to contaminate the record. For MASW Site #1, three hammer strike impacts were executed to create one seismic record. It is suggested that this be increased to at least 10 hammer strike impacts.
3) Optimize source and receiver spacing in order to develop higher quality dispersion curves. Due to time constraints on using the MASW equipment, seismic records were acquired at only the recommended source and receiver spacing given by Park, Miller, & Miura (2002). Their paper goes on to further recommend that spacing should be optimized based upon specific field conditions and that the ability to acquire seismic data over a range of different spacing distances adds to the robustness of analysis. Furthermore, additional functions within the *SurfSeis* software allow the

user to input a variety of seismic records based upon a variety of spacing distances, and the software developers recommend that this be done to enhance the accuracy of the analysis.

6.2 RPT/MASW Site #2 – Surfzone

Confidence in the accuracy of results of the MASW method at Site #2 was low. The seismic record for this site represents an unclear transmission or representation of the surface wave form and energy through the soil strata, and it was subject to contamination by outside signals and noise. (See *Figure 20*). Although the initial analysis of the data by the *SurfSeis* software indicated that the data quality was good, subsequent issues arose in processing due to the poor signal-to-noise ratio. This confirms initial concerns with the "noisy" seismic record in that the processing software had difficulty in identifying and performing dispersion and inversion for the surface wave signal because of competing signals and energy in the record. Although the software allowed processing to be carried out, there was very low confidence in the selection of the fundamental mode of dispersion that was used for inversion processing. Accordingly, the soil classification, developed shear wave velocity profile, derived blow count profile, and calculated bearing capacity for this site determined via the MASW method were considered unrealistic and not useful for comparison to the RPT method and pile driving logs.

There were several issues that arose when attempting to execute the MASW method at Site #2. These issues are listed below:

1) The seismic source intended for the marine sites did not actuate properly underwater. Therefore, the marine seismic source was not used, and the hammer and plate method

used for the terrestrial sites was implemented at Site #2. Accordingly, a very low amount of energy was imparted into the soil by the hammer and plate method because of an inability to get a full swing with the hammer through the shallow water column and onto the plate. This presented a problem for data acquisition in that a full-form or fully developed surface wave could not be produced because of the insufficient strike on the plate. This is confirmed in the seismic record presented in *Figure 20* in that the only clear energy trace acquired by the hydrophones was the result of the water wave action and energy in the surfzone and not the hammer strike.

2) As mentioned above, the water wave action in the surfzone dominated the seismic record making it difficult to clearly separate and identify the wave energy of the water wave action and wave energy of the seismic surface wave.
3) It was not possible to keep the hydrophone string in a straight line. As can be seen in *Figure 22* below, wave action in the surfzone forced the hydrophone string into a sinusoidal shape as opposed to the desired straight-line configuration.

Figure 22. Hydrophone string in sinusoidal configuration in surfzone

For accurate data acquisition, the MASW method requires that receivers used for acquisition are placed in a straight line away from the source so that signals can be acquired along a common, orthogonal transit. If the receivers are offset from a straight transit line, the time of signal acquisition is affected as the wave signal isn't travelling sequentially and straight down the line with known receiver offsets, but rather is received at varying times at various offsets depending upon where the receivers are located. This affects the processing of the signal as the analysis software assumes a straight-line geometry with known offsets between receivers to accurately calculate phase velocity and frequency dispersion. The lack of straight-line configuration during the testing at Site #2 further affected the quality of data acquired. Although weights were placed at intervals along the hydrophone carrier line, they were not sufficient to maintain a straight-line configuration.

The combination of the issues stated above contributed to the poor seismic record acquired at Site #2. As will be discussed below, similar issues contributed to the poor seismic record acquired at Site #3. The final section of this chapter discusses testing that was completed at UNF after the field visit to Virginia Beach, VA, in an attempt to mitigate these issues.

6.3 RPT/MASW Site #3 – Offshore

Confidence in the accuracy of results of the MASW method at Site #3 was low. The seismic record for this site represents an unclear transmission or representation of the surface wave form and energy through the soil strata, and it was subject to contamination by outside signals and noise. (See *Figure 21*). A quick field check of the seismic record was supported by the analysis that was done by the *SurfSeis* software which indicated that the data quality was determined to be poor, the risk of contamination from higher modes was determined to be high, and the signal-to-noise ratio for the record was assessed to be poor. Furthermore, the *SurfSeis* software was unable to detect a significant surface wave trace signal and indicated that any subsequent processing would not be a significant representation of the site. Although the software allowed inversion processing to continue, there was very low confidence in the selection of the fundamental mode of dispersion that was used for processing. Accordingly, the soil classification, developed shear wave velocity profile, derived blow count profile, and calculated bearing capacity for this site determined via the MASW method were considered unrealistic and not useful for comparison to the RPT method and pile driving logs.

There were several issues that arose when attempting to execute the MASW method at Site #3 that are very similar to those incurred at Site #2. These issues are listed below:

1) The seismic source intended for the marine sites did not actuate properly underwater, and the hammer and plate method used for the terrestrial sites was implemented at Site #3. Accordingly, a very low amount of energy was imparted into the soil by the hammer and plate method due to the inability to fully swing the hammer onto the plate. In fact, striking of the plate at Site #3 was only possible by a vertical lifting and then downward impact of the hammer onto the plate by forcing the hammer down through the 1 meter of water depth. This presented a problem similar to the one encountered at Site #2 in data acquisition in that a very insignificant amount of force and energy were actually imparted into the marine soils at Site #3.
2) Like Site #2, a current flow of incoming and outgoing waves in the offshore location dominated the seismic record making it difficult to clearly separate and identify current wave energy and seismic surface wave energy. Although the water current interference was less severe at Site #3, the seismic record still exhibits a clear pattern of outside signal and energy sources contaminating the record.
3) It was not possible to keep the hydrophone string in a straight line at Site #3. Although there was not as severe of a curvature of the hydrophone string as that at Site #2, the under current present at Site #3 still forced the hydrophone string into a sinusoidal shape.

A combination of the above issues contributed to the poor seismic record acquired at Site #3.

6.4 Summary of MASW Results at Site #1, Site #2, & Site #3

Utilizing the MASW method as a replacement for the RPT at terrestrial sites appears to be a reliable means to determine soil type, expected blow count, and expected bearing capacity. In the single site tested for this thesis, the MASW method provided a more accurate determination of the above parameters than the RPT. Furthermore, less equipment is needed to execute the MASW method, and the equipment requires less manpower and maintenance to set up and execute the method. Although use of the MASW method at terrestrial sites initially has been shown to be a reliable replacement for the RPT, additional testing and optimization of field setup, consideration of acquisition parameters, and increased familiarity with the method would increase confidence in relying on the MASW method in place of the RPT for terrestrial sites.

Utilizing the MASW method as a replacement for the RPT at marine sites currently is not a reliable means to determine soil type, expected blow count, and expected bearing capacity with confidence. There are significant problematic issues facing the implementation of MASW underwater as discussed in Sections 6.2 and 6.3 in this chapter. These are related specifically to the field setup and execution of data acquisition in a marine environment. The MASW method has been successfully executed underwater by previous authors (Kaufman, et. al., 2005), so it was concerning that it was not successful for this thesis. The problematic issues experienced with underwater implementation for this thesis can be grouped into the following categories:

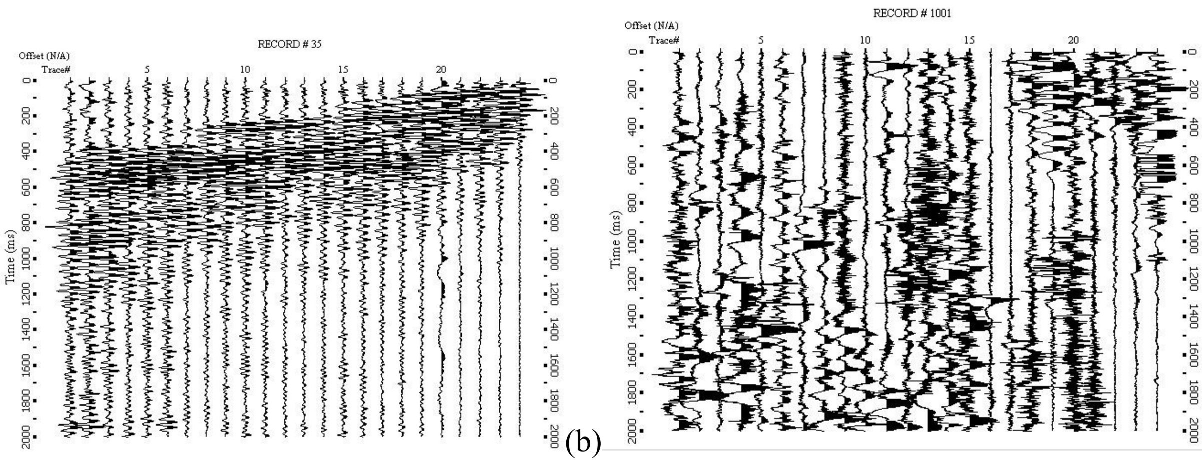
1) Utilizing a seismic source with sufficient energy to excite seismic surface waves of appropriate frequency and magnitude.

2) Reducing or overcoming the effect of passive background noise, signals, and energy in order to isolate the energy of the seismic surface waves for analysis.
3) Keeping the receiver string in a straight, common transit line.

In order to investigate whether overcoming these issues could produce a more reliable seismic record, field testing of the MASW method's hydrophones, both on land and underwater, was executed at the University of North Florida (UNF) in Jacksonville, FL, on 09 November 2018. This testing was completed as a follow-up to the testing conducted in Virginia Beach, VA, on 05-06 November 2018. The focus of this testing was:

1) Focus #1: To determine whether hydrophones oriented in a straight transit line on land could produce a reliable seismic record.
2) Focus #2: To determine whether hydrophones oriented in a straight transit line underwater, in still water conditions with little or no background noise or energy due to wave or current action, could produce a reliable seismic record.

The seismic record from the results of Focus #1 MASW testing compared with the seismic record for RPT/MASW Site #2 is shown in Figure 23 below.



(a) (b)

Figure 23. Comparison of seismic records. (a) Hydrophones on land UNF, Focus #1. (b) Hydrophones in surfzone, RPT/MASW Site #2

The seismic record from Focus #1 testing was compared to the seismic record for RPT/MASW Site #2 since the hydrophones for RPT/MASW Site #2 were at times exposed to air and were not underwater and thus comparable to the exposed/on land hydrophone setup for Focus #1. From visual inspection, the seismic record for Focus #1 shows a clear transmission of the seismic surface wave through the soil. Although not presented in this thesis, the dispersion and inversion of the seismic record for Focus #1 was successful and was indicated to be of high quality, low contamination, and with an excellent signal-to-noise ratio by the *SurfSeis* software. The comparison of the seismic record for Focus #1 to the record of RPT/MASW Site #2 indicates the following:

1) Keeping the receiver string in a straight-line assists in the quality of the seismic record.
2) A strong seismic source is essential for producing a high resolution, good quality record. The seismic source for Focus #1 was a hammer strike on a metal plate. (That

was the common method for terrestrial sites in this thesis). The seismic record for Focus #1 shows that, if a sufficient amount of energy is imparted into the soil, a distinctive seismic signature can be recognized.

3) The environment in which Focus #1 testing was conducted contained very little passive or background noise or energy that could contaminate the record. A means to mitigate this background noise is needed in a marine or surfzone environment like RPT/MASW Site #2 for an effective seismic record to be produced. Potential mitigations to accomplish this are:

   a. Using a seismic source with a very high energy output that can "dominate" the seismic record. When used in conjunction with stacking, this would allow the acquisition software to better recognize and process the seismic surface wave energy and "window" out the background noise.

   b. Executing the marine MASW method at multiple source offset and receiver distances to allow the *SurfSeis* software to better process and recognize the contribution of seismic surface wave energy to a seismic record from multiple records and reduce the contribution of background noise in the processing steps.

   c. Utilize frequency filtering options or techniques during post-acquisition analysis

Additionally, Focus #2 produced an underwater seismic record for subaqueous soils in a large lake on the UNF campus. The seismic record from the results of Focus #2 MASW testing is shown in Figure 24 below compared to the seismic record for RPT/MASW Site #3.

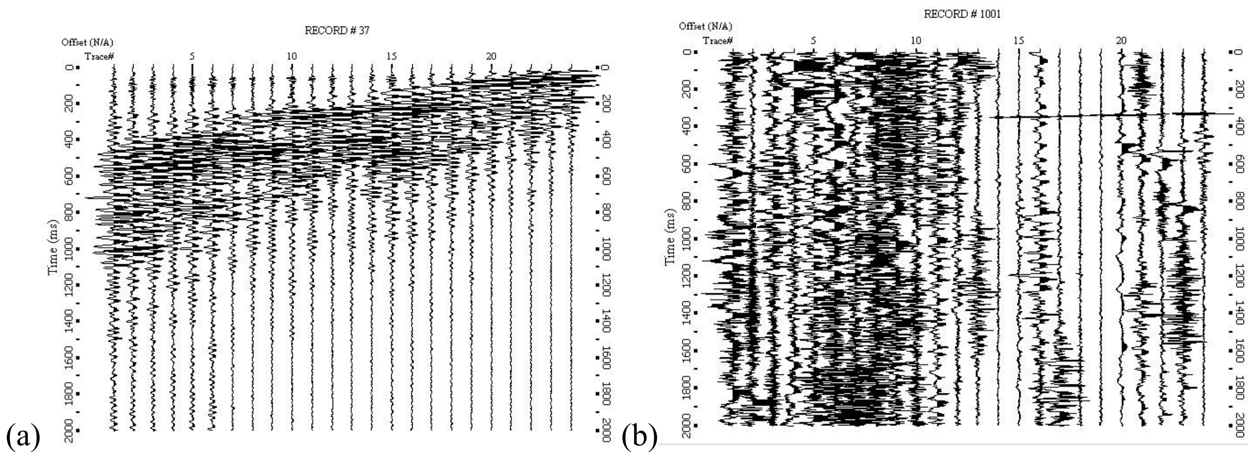


Figure 24. Comparison of seismic records. (a) Hydrophones underwater UNF, Focus #2. (b) Hydrophones offshore, RPT/MASW Site #3.

The seismic record from Focus #2 testing was compared with the seismic record for RPT/MASW Site #3 since both tests were executed underwater. From visual inspection, the seismic record for Focus #2 shows a clear transmission of the seismic surface wave through the subaqueous soil. Although not presented in this thesis, the dispersion and inversion of the seismic record for Focus #2 was successful and was indicated to be of high quality, low contamination, and with an excellent signal-to-noise ratio by the *SurfSeis* software. A comparison of the seismic record for Focus #2 with the record of RPT/MASW Site #3 indicates the following:

1) Utilizing hydrophones underwater can successfully produce a high-resolution seismic record.
2) The orientation of the receiver string in a straight-line assists in the quality of the seismic record.

3) As in Focus #1, a strong seismic source is essential for producing a high resolution/quality record. The seismic source for Focus #2 was a hammer strike on a metal plate 6-inches into the waterline of the lake on the UNF campus in 2-inches of water depth. It is necessary that an underwater seismic source produces at least as much energy as a 20-lb hammer strike on a metal plate.
4) The lake in which Focus #2 testing was conducted contained very little passive or background noise/energy, and the water in the lake was quiescent. This further reinforces the need to mitigate background noise in a marine or offshore environment, like that of RPT/MASW Site #3, in order for an effective seismic record to be produced. Potential mitigations to accomplish this are similar to the mitigations discussed above for Focus #1.

6.5 Recommendations for Improving System

The results from Focus #1 and Focus #2 testing were encouraging in that they showed that high-resolution seismic records can be produced underwater and that these records can be successfully processed to classify soils, predict blow counts, and estimate bearing capacity. Immediate MASW equipment and field setup improvements can be made and are recommended below:

1) Develop/procure an underwater seismic source that is reliable and whose associated seismic energy production underwater is greater than the seismic energy production associated with a 20-lb hammer strike on a metal plate on land.

2) Develop/procure a hydrophone string/streamer that is flexible enough to be transported but can also be made rigid enough during testing to allow for straight-line acquisition of seismic surveys underwater.

Outside of the desire for greater accuracy in soil property prediction, one of the driving factors in researching the MASW method as a potential replacement for the RPT was the desire to reduce the labor and equipment requirements needed to determine appropriate soil bearing capacity for ELCAS(M) erection.

The RPT method requires the equipment listed in Figure 25 below:

RPT Kit Components

Item and Description	Operational Quantity	Spares Quantity	Total Quantity
Breaker, Stanley Hydraulics BR67330	1	1	2
Seals kit, Stanley #04596	2	1	3
Bit, Brunner and Lay #T1910M0	10	1	11
Ground Rod Driver, Brunner and Lay #B32789	2	1	3
Drill Steel, 2 foot, Brunner and Lay #K1024AA	200	200	400
Coupling, Brunner and Lay #CC100R0	210	200	410
Torque Wrench, Sturtevant Richmont #855326	2	0	2
Torque Multiplier, Proto Model 6202	2	0	2
Shanks, Brunner and Lay #K101224	3	0	3
Extraction Tool	1	1-cylinder 1-valve	1
Socket, 7/8", 1/2" drive	1	3	4
Socket, 7/8", 3/4" drive	1	3	4
Wrenches, 7/8", open end	2	4	6

Figure 25. RPT equipment list

Also, not listed above, a hydraulic power unit (HPU) is required to drive the hydraulic breaker, or driver, for the steel rods used in RPT testing. This unit is outside of the base RPT equipment list due to the HPU being used for other diving operations and not solely for the RPT. This unit is shown in Figure 26 below.

Figure 26. Hydraulic power unit used for RPT operations

The total combined weight of all items required for the RPT is greater than a thousand pounds, and the equipment requires at least one operator to transport and operate the hydraulic breaker unit and two operators to set up and execute the RPT testing. Additionally, when the RPT is conducted offshore, a transport craft and shipboard personnel are required to execute the method. Lastly, the HPU and other associated RPT equipment all require routine inspection and maintenance to ensure that the equipment are in a ready-to-use condition.

In comparison, the equipment needed for the MASW method (as discussed in Chapter 5) is given below:

1) Hydrophone or geophone string (90 lbs)

2) Seismograph and associated cabling (50 lbs)
3) Seismic source, either terrestrial or marine (20 lbs)
4) Acquisition laptop and analysis software (10 lbs)
5) Battery power supply (40 lbs)

From solely a weight aspect, the equipment needed for the MASW method is much lighter and can be easily transported in two (2) 0.61 m x 0.61 m x 0.91 m Pelican cases and a backpack. These items can be transported in a personal vehicle versus the specialized transport truck and transport containers needed for the RPT equipment. The MASW method only requires two (2) operators to successfully transport the equipment and execute the testing. When common variables such as transport craft, shipboard personnel, and SCUBA diving equipment are factored in, executing the MASW method either on land or offshore is immensely more efficient from a labor and equipment standpoint.

Once the above immediate improvements are made, a direct comparison between the equipment and labor requirements of the RPT method and MASW method can be made and are shown in Table 7.

Table 7

MASW and RPT base system cost, labor, and field setup comparison

Investigation Method	Total System Cost ($)	Labor Required (# of personnel)	Time to setup and execute test at one location (hrs.)
MASW	$50,000	2	1.0
RPT	$40,000 (Does not include yearly maint. costs)	6	2.5

The base system cost is slightly higher for the MASW method than the RPT method but the MASW method does not require an approximately $1,000 in yearly maintenance costs that the RPT method requires. As such, it is assumed that the long-term cost for the RPT method is similar to the long-term cost of the MASW method. Based upon this comparison, the MASW method is competitive cost-wise with the RPT method and is more efficient from both the labor-required and time to execute field setup and testing standpoints.

6.6 Recommendations for Future Research

Based upon the confidence gained from the RPT/MASW Site #1 testing conducted on land, once the issues with executing the MASW method underwater are mitigated, and once additional field testing is executed and experience is accumulated, the MASW method has a strong potential to be used as a replacement for the RPT method both from an accuracy in soil property determination, as well as labor and equipment efficiency standpoints. In order to reach the level of confidence needed to replace the RPT with the MASW method, the following areas for future research are recommended:

1) Execute a series of MASW tests, RPT tests, and pile driving with supporting boring logs at the same location for a variety of sites with varying soil conditions for comparison.
2) Perform further research on measures to mitigate background noise associated with water waves and underwater currents to ensure that high resolution seismic records clearly capturing the seismic surface wave trace can be produced.

Chapter 7: Conclusions

This thesis utilized shear wave velocity profiles developed via the Multichannel Analysis of Surface Waves (MASW) method to ascertain relevant engineering properties of the terrestrial and marine soils of interest via correlations with the Cone Penetration Test (CPT) method of soil classification and geotechnical investigation. The correlation of shear wave velocity with CPT is potentially a powerful means to expand the utility of the MASW method for military geotechnical engineers. The developed shear wave velocity profiles and associated CPT correlations described in this thesis were utilized to classify soils, estimate pile driving blow counts, and estimate soil bearing capacity for piles in axial compression in order to determine whether the MASW method could successfully replace the Rapid Penetration Test (RPT) method that is presently utilized by the US Navy (USN).

The RPT method was developed in the mid-1990s and was based upon correlations to the CPT method reinforced by a series of soil studies specifically executed to calibrate the RPT method. However, further calibration and testing to increase the predictive capability and utility of the RPT method have not been undertaken since initial development. The MASW method was selected as a potential replacement for the RPT as it is a method that is actively being researched, and its reliability in providing accurate geotechnical information for soil sites has been well reviewed and documented. The MASW method was selected also because of its better efficiency and simplicity in setup, operation, analysis, and equipment needs, compared with the RPT method.

The MASW method was determined to be successful in characterizing the engineering properties of soils at a terrestrial site when compared with pile driving logs and data produced by the RPT method for the same site. The MASW method was not successful, however, in characterizing the engineering properties of soils at a set of marine sites that were either partially or fully submerged. The success of the MASW method on land suggests that the lack of success of the method underwater was due to equipment and field setup difficulties. Previous research that has successfully executed the MASW method in a marine environment (Kaufmann, et. al., 2005), in which hydrophones and a blank shotgun shell seismic source device were used to develop shear wave velocity profiles of shallow marine sediments, supports the conclusion that the lack of success in executing the MASW method as a part of this thesis was because of the above-mentioned issues. However, given the success of the MASW method at the terrestrial site and the success at executing the method underwater once operator and field setup errors were addressed, it can be concluded that the MASW method has the potential to be a reliable replacement for the RPT once further testing is completed and additional experience with the method is gained. Furthermore, the MASW method successfully addresses the desire to replace the RPT from a manpower and equipment efficiency standpoint.

Future work needed to ensure the reliability of the MASW method as a replacement for the RPT includes additional testing and comparison of the MASW method to the RPT method and ground truth boring logs at additional sites, additional optimization of the equipment and field setup utilized for the method, and additional means to ensure that high quality, high resolution seismic records are obtained for the sites under investigation.

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Appendix A

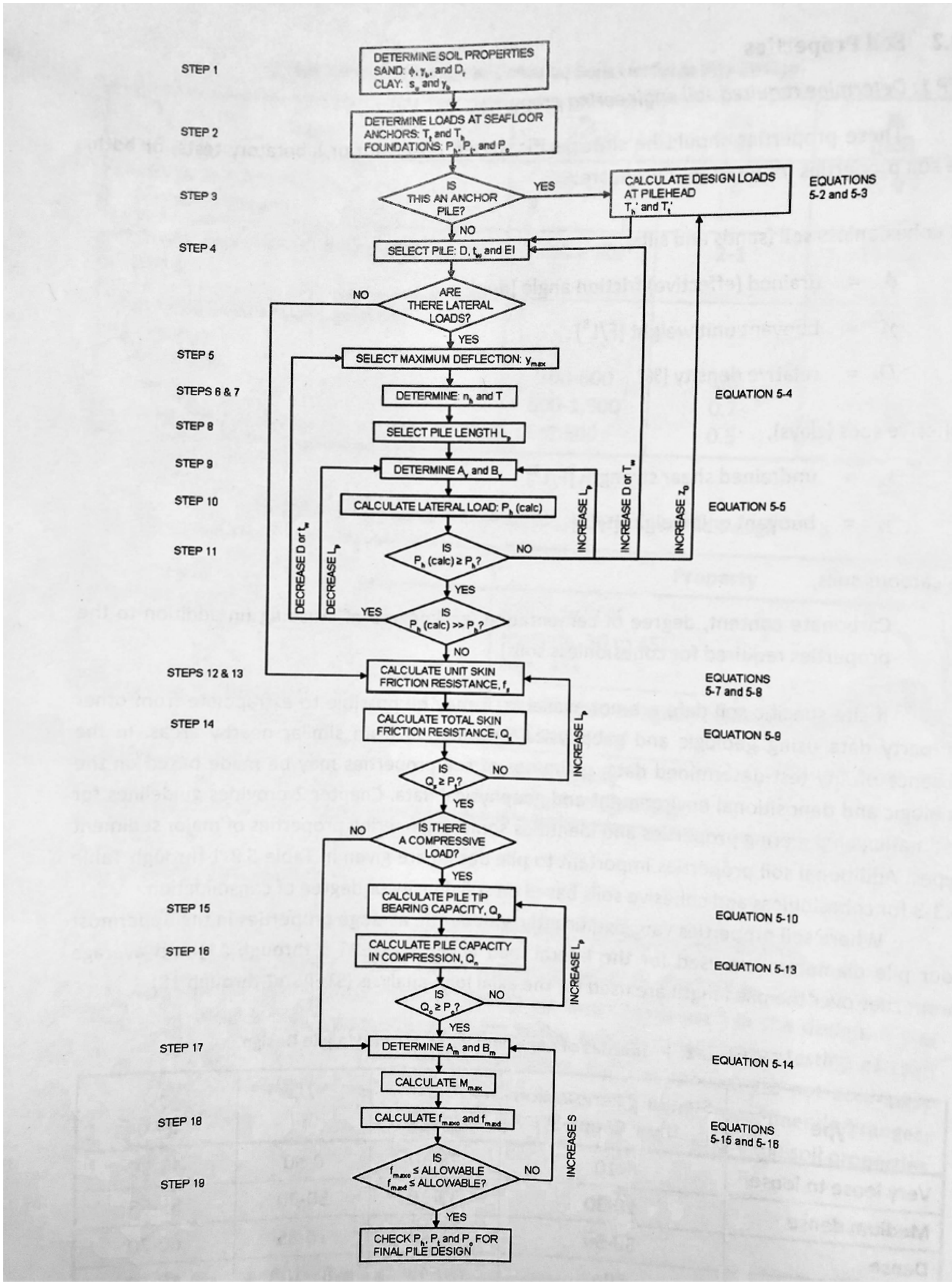


Figure 27. NAVFAC pile design flow chart from Thompson (2012)

Appendix B

ELCAS(M) pile blow count data, collected by sailors from Amphibious Construction Battalion TWO at the RPT sites, is given below.

DATE	TIME	PILE	BC	DEPTH
17-Apr-18	1450	RP 1-2	37	39'
16-Apr-18	1350	RP1-3	37	27'
20-Apr-18	1357	RP3-2	37	59'
16-Apr-18	1327	RP3-3	37	26'
19-Apr-18	1528	RP4-3	37	67'
19-Apr-18	1516	RP6-3	37	47'
23-Apr-18	1707	R1-1	37	50'
24-Apr-18	1529	R1-3	37	63'
23-Apr-18	1645	R3-1	37	46'
24-Apr-18	1515	R3-3	37	64'
26-Apr-18	1043	R4-3	37	62'
26-Apr-18	1052	R6-3	37	63'
		R7-3		
		R9-3		
		P4-1		
		P4-3		
		P6-1		
		P6-3		
		P9-1		
		P9-3		

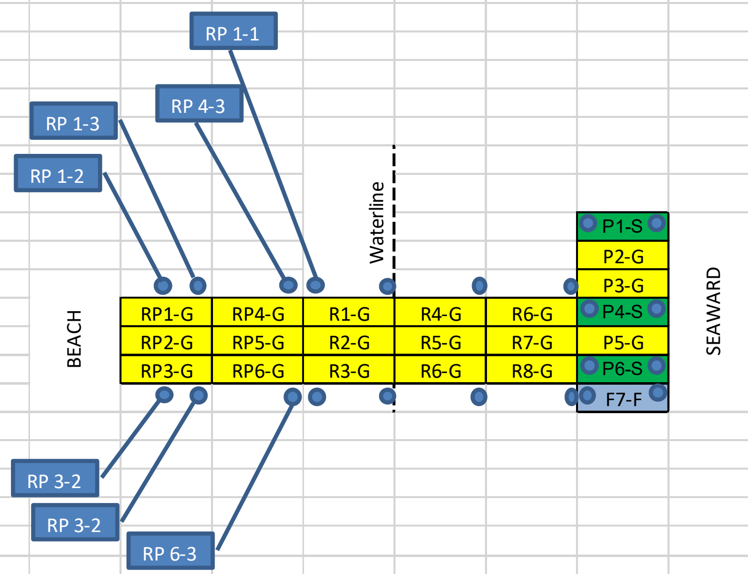


Figure 28. ELCAS(M) pile driving logs

Appendix C

RPT test data collected by divers from Underwater Construction Team ONE for RPT Site #1 is given below.

Test Data Calculation Worksheet

Rapid Penetration Test

	1	2	3	4	5	6	7	8
	Depth Interval	**Penetration Time**	**Torque**	**Rate**	**Penetration Factor**	**Torque Factor**	**Predicted Blow Counts**	**Estimated Bearing Cap.**
	(ft)	data sheet	(ft-lb)	(sec/ft)	Rate	Torque		
	as installed	(min,sec)			depth^1.5	depth^1.5		
RPT #1	2	:05	0	2.5	0.88	0.00	0.00	<50
Onshore	4	:19	30	9.5	1.19	3.75	<20	50.00
	6	:33	45	16.5	1.12	3.06	<20	72.00
	8	:26	40	13	0.57	1.77	<20	55.00
	10	:18	40	9	0.28	1.26	<20	50.00
	12	:22	45	11	0.26	1.08	<20	60.00
	14	:23	60	12.5	0.24	1.15	<20	70.00
	16	:30	50	15	0.23	0.78	<20	75.00
	18	:25	45	12.5	0.16	0.59	<20	60.00
	20	:26	60	13	0.15	0.67	21.00	73.00
	22	:28	55	24	0.23	0.53	26.00	76.00
	24	:45	75	22.5	0.19	0.64	29.00	110.00
	26	:39	75	19.5	0.15	0.57	26.00	100.00
	28	:43	90	21.5	0.15	0.61	31.00	
	30	:44	90	22	0.13	0.55	31.00	
	32	:40	100	20	0.11	0.55	34.00	
	34	:45	95	22.5	0.11	0.48	35.00	
	36	:49	110	24.5	0.11	0.51	37.00	90.00
	38	:49	145	24.5	0.10	0.62	48.00	
	40	:49	100	24.5	0.10	0.40		
	42	:47	110	23.5	0.09	0.40		
	44	1:08	200	34	0.12	0.69		
	46	1:25	170	42.5	0.14	0.54		
	48	2:10	170	65	0.20	0.51		
	49	4:00	150	120	0.35	0.44		
	< 10 ft			**Average**	**0.94**	**2.14**		
					Dense Sand and Gravel			
				Average	**0.17**	**0.65**		
			Medium Sand with reflections of clay and silt					

Figure 29. RPT data collected for RPT Site #1

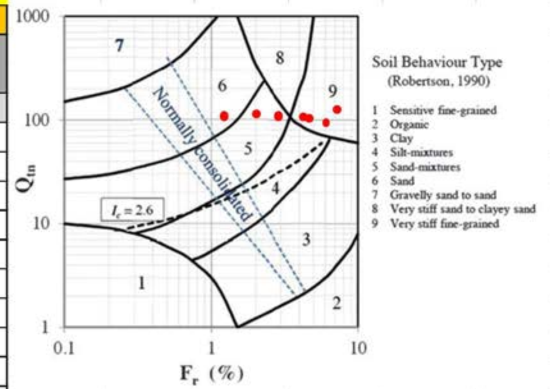
MASW calculations for RPT/MASW Site #1 are given below.

MASW_RPT Site #1 Calcs

Step 1: Soil Classification

a) Vs Data from SurfSeis. Must calculate fs and qc using equations 4.4 and 4.5

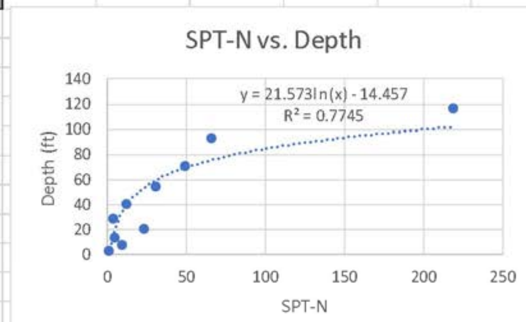
Depth (m)	Depth (ft)	Vs (m/s)	fs (kPa)	qc	Soil Type
1.107	3.6318899	78.797	1.661217	107.4612	Sand
2.491	8.1725724	193.033	4.345466	113.4087	Very stiff-fine grained
4.221	13.848426	151.623	3.066583	110.2963	Very stiff sand to clayey sand
6.383	20.941602	274.715	8.6425	114.0908	Very stiff-fine grained
9.086	29.809712	128.863	2.531929	107.3493	Sand mixtures
12.464	40.89239	214.817	5.220014	110.8003	Very stiff-fine grained
16.687	54.747377	307.89	11.42659	112.8146	---
21.965	72.063651	371.019	19.43998	113.4502	---
28.563	93.710633	415.563	28.28357	113.5668	---
35.704	117.13911	673.48	247.968	115.3202	---



Step 2: Blow Count Prediction

a) Vs and SPT-N Data from SurfSeis.

Depth (m)	Depth (ft)	Vs (m/s)	SPT-N	
1.107	3.63188988	78.797	1.026	
2.491	8.17257244	193.033	9.63	Using logarithmic regression,
4.221	13.84842564	151.623	5.268	37 blows/ft would occur at
6.383	20.94160172	274.715	23.28	approximately:
9.086	29.80971224	128.863	3.507	**63.44 ft.**
12.464	40.89238976	214.817	12.588	
16.687	54.74737708	307.89	30.957	
21.965	72.0636506	371.019	49.347	
28.563	93.71063292	415.563	65.516	
35.704	117.1391114	673.48	219	



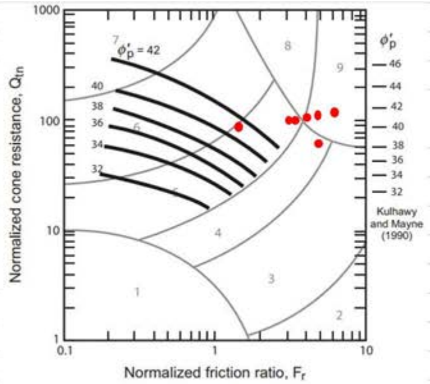
b) Data from pile driving logs

Depth (ft)	Blow Counts	
39	37	
27	37	
59	37	Based on average of all piles
26	37	driven from the beach to
67	37	prior to the surf zone,
47	37	average depth for 37 blows:
50	37	**51.08 ft.**
63	37	
46	37	
64	37	
62	37	
63	37	

Step 3: Calculate Bearing Capacity

a) Vs Data from SurfSeis. Must determine peak effective friction angle from chart in Figure 6. Calculate Relative Density using equation 4.7. Use published unit weights

Depth (m)	Depth (ft)	Vs (m/s)	Dr %	Friction Angle	Bulk UnitWeight (lbs/ft^3)
1.107	3.6318899	78.797	0.307032	40	110
2.491	8.1725724	193.033	0.324025	41	141
4.221	13.848426	151.623	0.315132	41	124
6.383	20.941602	274.715	0.325974	41	141
9.086	29.809712	128.863	0.306712	42	110
12.464	40.89239	214.817	0.316572	42	141
16.687	54.747377	307.89	0.322327	42	Assume 141
21.965	72.063651	371.019	0.324143	42	Assume 141
28.563	93.710633	415.563	0.324476	42	Assume 141
35.704	117.13911	673.48	0.329486	42	Assume 141



Typical Values of Soil Index Properties (from *NAVFAC 7.01*)

Soil Type	γ (lb/ft^3)	γ_{sub} (lb/ft^3)
Sand; clean, uniform, fine or medium	84 - 136	52 - 73
Silt; uniform, inorganic	81 - 136	51 - 73
Silty Sand	88 - 142	54 - 79
Sand; Well-graded	86 - 148	53 - 86
Silty Sand and Gravel	90 - 155	56 - 92
Sandy or Silty Clay	100 - 147	38 - 85
Silty Clay with Gravel; uniform	115 - 151	53 - 89
Well-graded Gravel, Sand, Silt and Clay	125 - 156	62 - 94
Clay	94 - 133	31 - 71
Colloidal Clay	71 - 128	8 - 66
Organic Silt	87 - 131	25 - 69
Organic Clay	81 - 125	18 - 62

b) Calculate bearing capacity utilizng NAVFAC formulas

Factor Safety =		2.0	Non critical case where soils not well known	
Pile Dimensions				
L =	38	ft	**Nq =**	28 From table 5.3-4 Thompsoon (2012)
Dia. =	2	ft		

a) Calculate effective over burden pressure (σ'vo). Thompson (2012) step 14, pg 5-40

2679 lb/ft^2

b) Calculate skin frictional resistance in compression (fs). Thompson (2012) step 20, pg 5-42

1413.1399 lb/ft^2

c) Calculate pile tip bearing capacity (Qt). Thompson (2012) step 23, pg 5-42

471075.36 lbs

d) Calculate total pile capacity in compression, Qt + Qs. Thompson (2012), step 24, pg 5-42

808307.07 lbs

Figure 30. MASW bearing capacity calculations for RPT/MASW Site #1

Appendix D

RPT test data collected by divers from Underwater Construction Team ONE for RPT Site #2 is given below.

	Test Data Calculation Worksheet							
	Rapid Penetration Test							
RPT #2	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Surfzone	**Depth Interval**	**Penetration Time**	**Torque**	**Rate**	**Penetration Factor**	**Torque Factor**	**Predicted Blow Counts**	**Estimated Bearing Cap.**
	(ft)	data sheet	(ft-lb)	(sec/ft)	Rate	Torque		
	as installed	(min,sec)			depth^1.5	depth^1.5		
	2	:05	0	2.5	0.88	0.00	0.00	<50
	4	:22	20	11	1.38	2.50	<15	
	6	:42	20	21	1.43	1.36		
	8	:33	40	16.5	0.73	1.77		
	10	:35	50	17.5	0.55	1.58		
	12	:28	50	14	0.34	1.20		
	14	:34	60	17	0.32	1.15		
	16	:36	50	18	0.28	0.78		
	18	:56	80	28	0.37	1.05	37.00	
	20	1:12	120	36	0.40	1.34	>37	
	22	1:15	100	37.5	0.36	0.97	>37	
	24	1:03	100	31.5	0.27	0.85	>37	
	26	:58	80	29	0.22	0.60		
	28	:57	90	28.5	0.19	0.61		
	30	:57	80	28.5	0.17	0.49		
	32	1:05	100	32.5	0.18	0.55		
	34	1:15	100	37.5	0.19	0.50		
	36	1:00	100	30	0.14	0.46		
	38	1:03	100	31.5	0.13	0.43		
	40	1:17	100	38.5	0.15	0.40		
	42	1:19	135	39.5	0.15	0.50		
	44	1:19	135	39.5	0.14	0.46		
	46	1:15	135	37.5	0.12	0.43		
	48	1:06	135	33	0.10	0.41		
	50	1:03	135	31.5	0.09	0.38		
	52	1:18	165	39	0.10	0.44		
	54	1:30	200	45	0.11	0.50		
	56	2:30	175	75	0.18	0.42		
	58	2:43	200	81.5	0.18	0.45		
	60	2:35	230	77.5	0.17	0.49		
	62	2:30	240	75	0.15	0.49		
	< 10 ft			**Average**	**1.10**	**1.41**		
					Dense Sand and Gravel			
				Average	**0.21**	**0.66**		
			Medium Sand with reflections of clay and silt					

Figure 31. RPT data collected for RPT Site #2

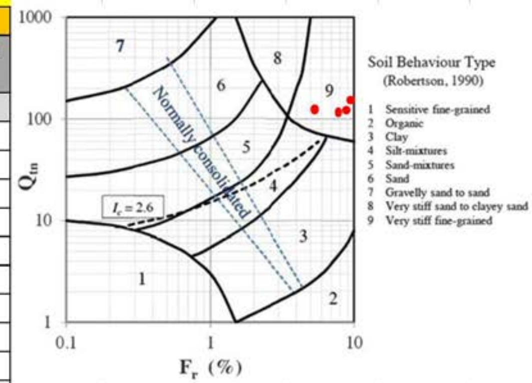
MASW calculations for RPT/MASW Site #2 are given below.

MASW_RPT Site #2 Calcs

Step 1: Soil Classification

a) Vs Data from SurfSeis. Must calculate fs and qc using equations 4.4 and 4.5 and use chart in Figure 5 for soil classification

Depth (m)	Depth (ft)	Vs (m/s)	fs (kPa)	qc	Soil Type
0.8	2.624672	289.455	9.784172	119.1102	Very stiff-fine grained
1.8	5.905512	276.044	8.739726	116.9242	Very stiff-fine grained
3.05	10.006562	168.573	3.536865	111.8639	Very stiff-fine grained
4.61	15.124672	299.259	10.62587	115.4241	Very stiff-fine grained
6.55	21.489502	858.166	1173.676	119.7	---
8.99	29.494752	1019.597	4567.597	119.0611	---
12.04	39.501314	595.242	128.3461	117.2859	---
15.85	52.001314	220.69	5.484555	110.4982	Very stiff-fine grained
20.61	67.618112	455.313	39.52278	114.7967	---
25.76	84.514438	988.97	3529.598	116.694	---

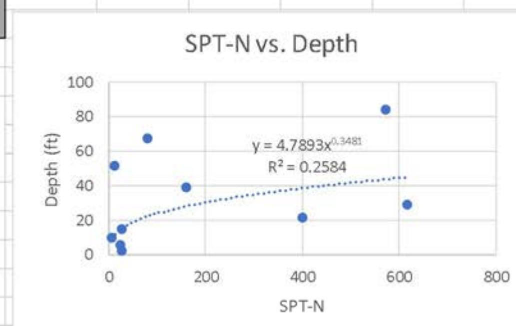


Step 2: Blow Count Prediction

a) Vs and SPT-N Data from SurfSeis.

Depth (m)	Depth (ft)	Vs (m/s)	SPT-N
0.8	2.624672	289.455	26.53
1.8	5.905512	276.044	23.561
3.05	10.006562	168.573	6.866
4.61	15.1246724	299.259	28.83
6.55	21.489502	858.166	401.51
8.99	29.4947516	1019.597	617.786
12.04	39.5013136	595.242	160.877
15.85	52.001314	220.69	13.4654
20.61	67.6181124	455.313	82.3249
25.76	84.5144384	988.97	572.429

Using power law regression, 37 blows/ft would occur at approximately (ft): **16.83**

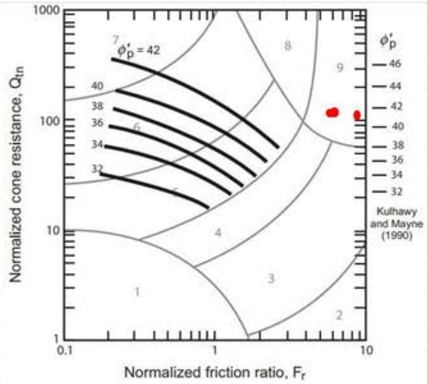


b) Data from pile driving logs

Depth (ft)	Blow Counts
39	37
27	37
59	37
26	37
67	37
47	37
50	37
63	37
46	37
64	37
62	37
63	37

Based on average of all piles driven from the beach to surf zone, average depth for 37 blows: **51.08 ft.**

Step 3: Calculate Bearing Capacity					
a) Vs Data from SurfSeis. Must determine peak effective friction angle from chart in Figure 6. Calculate Relative Density using equation 4.7. Use published unit weights					
Depth (m)	Depth (ft)	Vs (m/s)	Dr %	Friction Angle	Bulk UnitWeight (lbs/ft^3)
0.8	2.624672	289.455	0.340315	40	62
1.8	5.905512	276.044	0.334069	41	62
3.05	10.006562	168.573	0.319611	41	62
4.61	15.124672	299.259	0.329783	41	62
6.55	21.489502	858.166	0.342	---	62
8.99	29.494752	1019.597	0.340174	---	62
12.04	39.501314	595.242	0.335103	---	Assume 62
15.85	52.001314	220.69	0.315709	42	Assume 62
20.61	67.618112	455.313	0.32799	---	Assume 62
25.76	84.514438	988.97	0.333411	---	Assume 62
b) Calculate bearing capacity utilizng NAVFAC formulas					



Typical Values of Soil Index Properties (from *NAVFAC 7.01*)

Soil Type	γ (lb/ft^3)	γ_{sub} (lb/ft^3)
Sand; clean, uniform, fine or medium	84 - 136	52 - 73
Silt; uniform, inorganic	81 - 136	51 - 73
Silty Sand	88 - 142	54 - 79
Sand; Well-graded	86 - 148	53 - 86
Silty Sand and Gravel	90 - 155	56 - 92
Sandy or Silty Clay	100 - 147	38 - 85
Silty Clay with Gravel; uniform	115 - 151	53 - 89
Well-graded Gravel, Sand, Silt and Clay	125 - 156	62 - 94
Clay	94 - 133	31 - 71
Colloidal Clay	71 - 128	8 - 66
Organic Silt	87 - 131	25 - 69
Organic Clay	81 - 125	18 - 62

Factor Safety =	2.0	Non critical case where soils not well known	
Pile Dimensions			
L =	38 ft	Nq =	28 From table 5.3-4 Thomposon (2012)
Dia. =	2 ft		

a) Calculate effective over burden pressure (σ'vo). Thompson (2012) step 14, pg 5-40

1178 lb/ft^2

b) Calculate skin frictional resistance in compression (fs). Thompson (2012) step 20, pg 5-42

621.38067 lb/ft^2

c) Calculate pile tip bearing capacity (Qt). Thompson (2012) step 23, pg 5-42

207139.52 lbs

d) Calculate total pile capacity in compression, Qt + Qs. Thompson (2012), step 24, pg 5-42

355425.8 lbs

Figure 32. MASW bearing capacity calculations for RPT/MASW Site #2

Appendix E

RPT test data collected by divers from Underwater Construction Team ONE for RPT Site #3 is given below.

	Test Data Calculation Worksheet							
	Rapid Penetration Test							
RPT #3	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Offshore	**Depth Interval**	**Penetration Time**	**Torque**	**Rate**	**Penetration Factor**	**Torque Factor**	**Predicted Blow Counts**	**Estimated Bearing Cap.**
	(ft)	data sheet	(ft-lb)	(sec/ft)	Rate	Torque		
	as installed	(min,sec)			depth^1.5	depth^1.5		
	2	:04	0	2	0.71	0.00	0.00	
	4	:22	20	11	1.38	2.50	<15	
	6	:33	30	16.5	1.12	2.04		
	8	:38	40	19	0.84	1.77		
	10	:35	50	17.5	0.55	1.58		
	12	:35	40	17.5	0.42	0.96		
	14	:35	50	17.5	0.33	0.95		
	16	:47	60	23.5	0.37	0.94		
	18	:47	50	23.5	0.31	0.65		
	20	:40	50	20	0.22	0.56		
	22	:35	60	17.5	0.17	0.58		
	24	:40	60	20	0.17	0.51		
	26	:40	60	20	0.15	0.45		
	28	:40	55	20	0.13	0.37		
	30	:47	130	23.5	0.14	0.79	>37	
	32	:48	80	24	0.13	0.44		
	34	:50	120	25	0.13	0.61	>37	100.00
	36	:59	140	34.5	0.16	0.65	>37	
	38	1:03	145	31.5	0.13	0.62		
	40	1:46	170	53	0.21	0.67		
	42	2:27	200	73.5	0.27	0.73		
	44	5:00	250	150	0.51	0.86		
	< 10 ft			**Average**	**1.01**	**1.58**		
					Dense Sand and Gravel			
	>10 ft			**Average**	**0.25**	**0.72**		
			Medium Sand with reflections of clay and silt					

Figure 33. RPT data collected for RPT Site #3

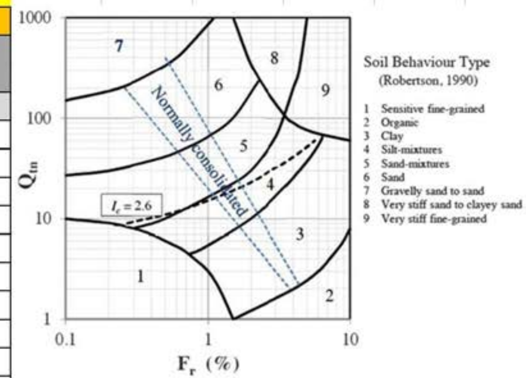
MASW calculations for RPT/MASW Site #3 are given below.

MASW_RPT Site #3 Calcs

Step 1: Soil Classification

a) Vs Data from SurfSeis. Must calculate fs and qc using equations 4.4 and 4.5 and use chart in Figure 5 for soil classification

Depth (m)	Depth (ft)	Vs (m/s)	fs (kPa)	qc	Soil Type
0.562	1.8438321	729.548	397.5229	125.1091388	Indeterminate
1.264	4.1469818	903.243	1715.28	123.5862348	---
2.142	7.0275593	1046.414	5724.295	122.3594318	---
3.24	10.629922	937.104	2280.972	121.4051798	---
4.612	15.131234	473.471	46.04974	118.3497298	---
6.327	20.757875	690.122	285.2551	119.2817629	---
8.471	27.791996	1413.028	125298.1	118.4100593	---
11.151	36.584647	1821.897	3914153	116.0997086	---
14.501	47.575461	2052.955	27372299	114.3317865	---
18.126	59.468506	3034.05	1.06E+11	107.8418294	---

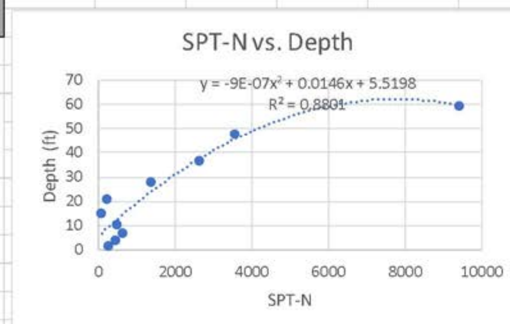


Step 2: Blow Count Prediction

a) Vs and SPT-N Data from SurfSeis.

Depth (m)	Depth (ft)	Vs (m/s)	SPT-N
0.562	1.84383208	729.548	267.548
1.264	4.14698176	903.243	456.322
2.142	7.02755928	1046.414	659.202
3.24	10.6299216	937.104	500.298
4.612	15.13123408	473.471	90.7809
6.327	20.75787468	690.122	232.849
8.471	27.79199564	1413.028	1396.82
11.151	36.58464684	1821.897	2636.79
14.501	47.57546084	2052.955	3553.98
18.126	59.46850584	3034.05	9436.7

Using ploynomial regression, 37 blows/ft would occur at approximately (ft):
6.1



b) Data from pile driving logs

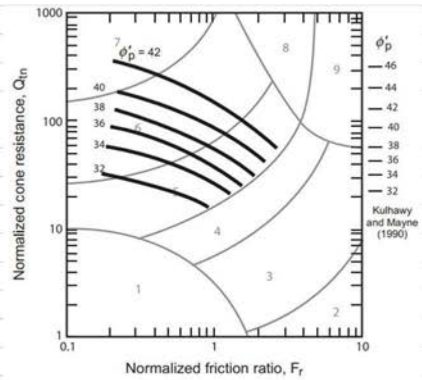
Depth (ft)	Blow Counts
39	37
27	37
59	37
26	37
67	37
47	37
50	37
63	37
46	37
64	37
62	37
63	37

Based on average of all piles driven from the beach to surf zone, average depth for 37 blows:
51.08 ft.

Step 3: Calculate Bearing Capacity

a) Vs Data from SurfSeis. Must determine peak effective friction angle from chart in Figure 6. Calculate Relative Density using equation 4.7. Use published unit weights

Depth (m)	Depth (ft)	Vs (m/s)	Dr %	Friction Angle	Bulk UnitWeight (lbs/ft^3)
0.562	1.8438321	729.548	0.357455	Indeterminate	Assume 62
1.264	4.1469818	903.243	0.353104	Assume 42	Assume 62
2.142	7.0275593	1046.414	0.349598	---	Assume 62
3.24	10.629922	937.104	0.346872	---	Assume 62
4.612	15.131234	473.471	0.338142	---	Assume 62
6.327	20.757875	690.122	0.340805	---	Assume 62
8.471	27.791996	1413.028	0.338314	---	Assume 62
11.151	36.584647	1821.897	0.331713	42	Assume 62
14.501	47.575461	2052.955	0.326662	---	Assume 62
18.126	59.468506	3034.05	0.30812	---	Assume 62



Typical Values of Soil Index Properties (from *NAVFAC 7.01*)

Soil Type	γ (lb/ft^3)	γ_{sub} (lb/ft^3)
Sand; clean, uniform, fine or medium	84 - 136	52 - 73
Silt; uniform, inorganic	81 - 136	51 - 73
Silty Sand	88 - 142	54 - 79
Sand; Well-graded	86 - 148	53 - 86
Silty Sand and Gravel	90 - 155	56 - 92
Sandy or Silty Clay	100 - 147	38 - 85
Silty Clay with Gravel; uniform	115 - 151	53 - 89
Well-graded Gravel, Sand, Silt and Clay	125 - 156	62 - 94
Clay	94 - 133	31 - 71
Colloidal Clay	71 - 128	8 - 66
Organic Silt	87 - 131	25 - 69
Organic Clay	81 - 125	18 - 62

b) Calculate bearing capacity utilizng NAVFAC formulas

Factor Safety =	2.0	Non critical case where soils not well known		
Pile Dimensions				
L =	38 ft	**Nq =**	28	From table 5.3-4 Thomposon (2012)
Dia. =	2 ft			

a) Calculate effective over burden pressure (σ'vo). Thompson (2012) step 14, pg 5-40

1178 lb/ft^2

b) Calculate skin frictional resistance in compression (fs). Thompson (2012) step 20, pg 5-42

621.38067 lb/ft^2

c) Calculate pile tip bearing capacity (Qt). Thompson (2012) step 23, pg 5-42

207139.52 lbs

d) Calculate total pile capacity in compression, Qt + Qs. Thompson (2012), step 24, pg 5-42

355425.8 lbs

Figure 34. MASW bearing capacity calculations for RPT/MASW Site #3

Vita

Lieutenant (LT) William Fletcher was born in Chattanooga, Tennessee and spent his formative years in Fernandina Beach, Florida. He graduated from Fernandina Beach High School in 2002. He graduated from the University of North Florida in 2007 with a BS in Civil Engineering. He worked for two and one-half years at the consulting engineering firm, Mittauer & Associates, Inc., in Orange Park, Florida executing funding acquisition, design, bidding, and contract administration services for numerous water and wastewater projects throughout Florida. He entered the US Navy in Jacksonville, FL, on 22 July 2009. His first duty station was onboard Naval Air Facility, Atsugi, Japan, where he served as the Assistant Public Works Officer, Production Division Director, and Division Officer overseeing 35 Public Works Department (PWD) Seabees. LT Fletcher transferred to US Naval Mobile Construction Battalion ONE in Gulfport, Mississippi in March 2013. His assignments in the Battalion included BRAVO Company Commander, Naval Construction Force Liaison Officer to the Kingdom of Cambodia, and Operations Department Exercise Control Group Lead. LT Fletcher next reported to NAVFAC MILPERS DET in Millington, Tennessee, in April 2015. He served as the Deputy Accessions Officer managing outreach and awareness activities directed toward the Fleet, college students, and the general populace. Since July 2017, LT Fletcher has been a graduate student in the Master of Civil/Coastal Engineering program at the University of North Florida in Jacksonville, Florida. His career highlights include serving alongside the Atsugi Seabees in assisting with humanitarian assistance/disaster relief efforts throughout Operation Tomodachi in the aftermath of the Great Tohoku Earthquake and subsequent tsunami in Japan in March 2011 and planning and executing maternity and sanitation facilities construction for the citizens of

Cambodia. He is qualified as a Professional Engineer (PE) in the State of Florida. LT Fletcher is married to the former Sarah A. Hudson of Jacksonville, Florida. He and his wife have a ten-year old daughter named Olive and an eight-year old son named Hiro. His interests include playing rugby, camping, hiking, reading, and being with family and friends.